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Optimisation of narrowband optical filters for 10 Gbit/s directly modulated laser transmitters

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Filtering of the chirped signal from a directly modulated laser with the narrowband optical filter with a high roll-off allows to in-crease the dispersion tolerance of the transmitter substantially. In the paper, the influence of the parameters of the filter on the performance of the fibre link is analysed. Investigations are carried out for both band-pass and band-stop filters. Basing on the numerical modelling of the fibre link, the parameters of the filter are searched that give the smallest dispersion penalty. Theoretical investigations are supported by hardware experiments confirming correctness of applied methods and models.

Keywords: directly modulated laser, optical filtering, dispersion tolerance, dispersion penalty.

1. Introduction

Recently an increased interest is observed in the fibre optic transmission systems operating in the metropolitan area with the data rate around 10 Gbit/s. Direct modulation of the semiconductor lasers is attractive for such applications because it enables reducing the transmitter complexity, thus lowering its cost. Other alternatives typically used in high-speed laser transmitters, as Mach–Zehnder (MZ) or electroabsorption (EA) modulators, require substantial amount of driving power and suffer from relatively high insertion loss [1]. It is known that many modern multi-quantum well (MQW) distributed feedback (DFB) lasers are capable of modulation with the speed in the range of 10 Gbit/s [2, 3]. Examples are known from the literature where devices designed for 2.5 Gbit/s systems were successfully used at 10 Gbit/s data rate [4]. Modulation with the data rate as high as 40 Gbit/s was also reported [5, 6].

Because the electrical current flowing through the directly modulated laser (DML) influences the optical density of its active region, thus the frequency of the generated optical carrier is affected by some chirp. Despite the complexity of the process of generating the light by the MQW DFB laser, it is commonly accepted to describe the chirp assuming only two components [7, 8]. The first one, called the adiabatic chirp, results in the frequency shift directly proportional to the optical power of the laser. The second one, called the dynamic chirp, is related to the time derivative of the laser power. The chirp parameters are rarely given by the laser manufacturers, the techniques however exist to determine them from the measurements [9–11].

Laser chirp interacts with the dispersion of the optical fibre resulting in distortions of the data signal propagating along it. Because of that, the transmission distance of the link is severely limited, typically to below 20 km of the standard single-mode fibre (SMF) operating in 1550 nm wavelength range. To alleviate this dispersion limit, fibres with low or negative dispersion coefficient may be used. Such fibres however, are not always available in existing installations. Applying various schemes of dispersion management, on the other hand, requires using dispersion compensating devices (based either on special fibres or Gires–Tournois etalons [12]) that introduce substantial attenuation of the optical signal, are bulky and increase the cost of the link. Techniques were also proposed that use electronic equalization together with forward error correction to overcome the effects caused by dispersion-induced distortions [13].

The other possibility that may also be pointed out is to process the optical signal with the optical filter. Using such filters for narrowing/shaping the laser optical spectrum broadened by chirping [14–18], converting the laser chirp into the intensity modulation on the slope of the filters characteristic [19, 20] or using the filter as the dispersion compensator [21] are known from the literature. Possible extension of transmission distance resulting from passing properly located DML spectrum through the standard dense wavelength division (DWDM) multiplexer is described in [22]. Performance improvement resulting from applying both optical filtering and electronic equalization has been also investigated recently [23].

However, it was observed by the authors that positioning of the central wavelength of the DML on the edge of the filter with sufficiently high roll-off increases greatly the tolerance of the DML to the dispersion of the fibre [24]. Such filtering method works for both band-pass and band-stop filters and gains from modifying the chirp of the optical signal. It was also checked that described method is greatly insensitive to the particular dispersion of the fibre link. In this paper, the influence and available gain of optical filtering on the slope of a high roll-off filter for band-pass and band-stop filters are examined. The experimental results, supporting the theoretical predictions, are also presented.

2. Optical filtering of the DML output signal

The position of the optical spectrum relative to the characteristics of the filter affects the shape of the DML-generated signal that appears at the output of the dispersive fibre. Both attenuation and group delay characteristics of the filter are important for processing the signal. In Figure 1**a** typical transmission/group delay characteristics of the band-pass filter are shown with the arrows pointing at some interesting locations of the DML spectrum. In Figure 1**b** the eye diagrams corresponding to these locations, simulated for 10 Gbit/s DML operating at 1550 nm, are plotted at the output of the filter and the output of the fibre link with dispersion of 850 ps/nm (~50 km of standard SMF).

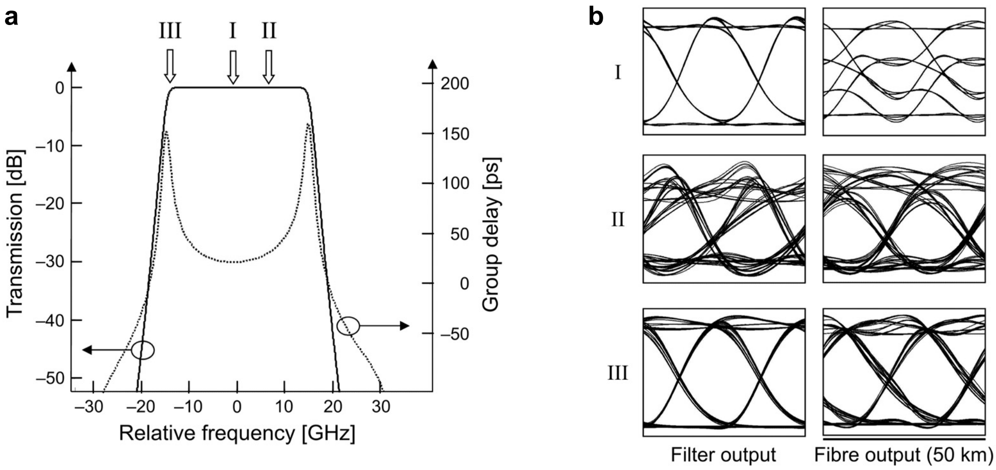

Fig. 1. Location of the laser spectrum relative to the characteristics of the optical filter (**a**) and resulting eye diagrams (**b**).

Position designated as I may be regarded as typical filtering operation, where the spectrum of the signal is located in the centre of the characteristic of the filter. In this case, the eye diagram at the output of the filter is actually the same as the signal generated by DML. The signal at the output of the link exhibits substantial distortions caused by interaction of chirp and dispersion. Because the bandwidth of the filter is substantially broader than the spectrum of the signal, filtering has almost no effect on the output eye diagram.

When the spectrum of the signal is located in position II, some improvement in the eye diagram at the output of the link is observed. The filter attenuation is essentially flat in this position but the group delay displays some positive slope there, being opposite to that resulting from the dispersion of the fibre. Thus the filter operates here as the dispersion compensator [21]. Signal observed just at the output of the filter is distorted, but this in fact may be regarded as some predistortion, that is further "equalized" by the dispersion of the fibre. Because the group delay of the filter is non-linear around position II, the perfect compensation is generally impossible. This presents serious disadvantages when using optical filters operating in such dispersion--compensating regime.

Much better results are observed when the spectrum of the signal is located in position III, *i.e.*, on the rising slope of the filter, closely to its –3 dB power attenuation point. Signals observed at the output of the filter and at the output of the fibre are very similar and exhibit only minor distortions. Both eye diagrams are well opened, with the crossing points located in the middle of the eye. The operation of the filter in this mode was discussed in [24] where it was pointed out that the improvement in the quality of the signal is due to modification of the chirp associated with the optical signal. In this case, the filter is optimised to the laser chirping characteristics only, thus no adjustment is required to the particular dispersion of the fibre link. In the following sections, the available gain resulting from filtering of the optical signal on the slope of the filter are considered. In addition, the optimisation of the filter parameters is performed.

3. Model of the fibre link

For the lack of a rigorous theoretical model how the parameters of the filter affect the performance of the fibre link, we decided to use optimisation methods to perform thorough evaluation.

The chirp of the DML was assumed to follow the commonly accepted model [7, 8] given by the equation:

$$\Delta\nu(t) = \frac{\alpha}{4\pi}\left[\kappa P_\lambda(t) + \frac{1}{P_\lambda(t)}\frac{\mathrm{d}P_\lambda(t)}{\mathrm{d}t}\right] \tag{1}$$

where: $\Delta\nu(t)$ is the frequency shift from the nominal wavelength of the DML caused by the direct modulation, $P_\lambda(t)$ is the instantaneous value of optical power, α is the so-called line enhancement factor and κ is the coefficient of the adiabatic chirp. In further hardware experiments, the laser NLK1551SSC by NEL, rated at 10 Gbit/s with the peak power of 4 mW and the chirping parameters $\alpha = 1.8$ and $\kappa = 6.3$ GHz/mW, measured accordingly to the method presented in [11] will be used. Such parameters are also assumed in the simulations that follow. The central wavelength of the laser was 1550.12 nm.

The complex envelope of the optical field generated by the DML is modeled accordingly to the equation:

$$E(t) = \sqrt{P_\lambda(t)}\,\exp\left[j\Phi(t)\right] \tag{2}$$

where $\Phi(t)$ denotes the instantaneous value of the phase and equals to the time integral of the chirp calculated from Eq. (1).

For the sake of generality, two types of the characteristics of the optical filters are considered herein – the band-pass and the band-stop. The first one may be regarded as a prototype for the dielectric thin film filters (TFF) and Bragg gratings operating in reflection regime, whereas the second one for Bragg gratings operating in transmission or TFFs operating in reflection. The amplitude characteristic (for the envelope) of the band-pass filter is defined by the equation:

$$\left|H_{\mathrm{BP}}(f)\right|^2 = \frac{1}{1 + \left|\dfrac{f - B/2}{B/2}\right|^N} \tag{3}$$

where the parameters N and B allow to change independently the roll-off of the filter and its bandwidth. Characteristics of the filter given by Eq. (3) were defined in

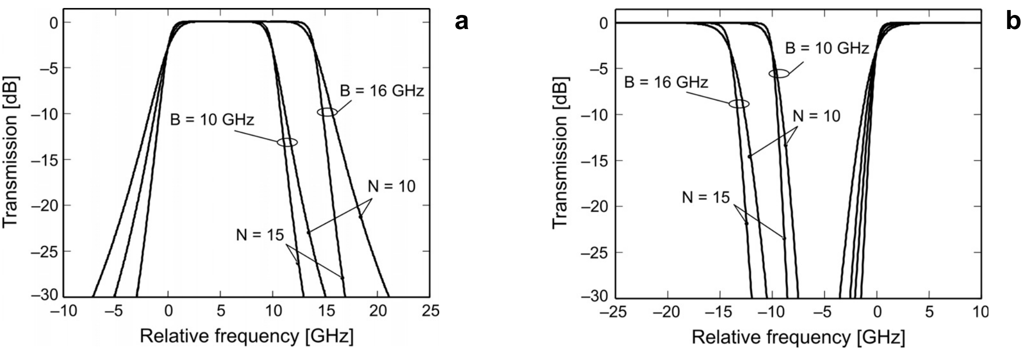

Fig. 2. Example characteristics of the filters: band-pass (**a**) and band-stop (**b**).

the way to make the rising slopes for different values of B and N to cross for the relative frequency $f = 0$ at the –3 dB point. The band-stop characteristics are defined as the complement of the characteristic (3):

$$\left|H_{\mathrm{BS}}(f)\right|^2 = 1 - \left|H_{\mathrm{BP}}(f)\right|^2 \tag{4}$$

Examples of characteristics obtained from Eqs. (3) and (4) are presented in Fig. 2.

To calculate the response of the filter, its phase characteristics are also necessary. Because many types of optical filters are minimum-phase systems [25], this assumption was accepted herein as well. Thus, the phase characteristics were calculated from the filter amplitude response given by (3) or (4) using the Kramers–Kronig relation [8, 26, 27]. The output signal of the filter was calculated by multiplying the Fourier transform of the DML complex envelope (2) by the characteristic of the filter (3) or (4) and taking the inverse Fourier transform of the product.

To account for the dispersive properties of the fibre, its impulse response is used in the form given by [25]:

$$h(t) = \sqrt{j \frac{c}{z D \lambda^2}} \exp\left(-j \frac{\pi c}{z D \lambda^2} t^2\right) \tag{5}$$

where: λ is the nominal wavelength of the DML, z is the length of the fibre, c is the speed of light, $D = \mathrm{d}(1/v_g)/\mathrm{d}\lambda$ is the dispersion coefficient and v_g is the group velocity of the light envelope in the fibre. In the calculations, the constant delay introduced by the fibre and its attenuation were neglected, as these factors do not influence further results.

The signal at the output of the fibre was calculated as the convolution of the impulse response of the fibre and the envelope of the signal entering the fibre. Finally, the output power as seen by the receiver is simply the square of the envelope at the output of the fibre. For all simulations the standard Matlab software packages were used. The block diagram of the simulation setup is shown in Fig. 3.

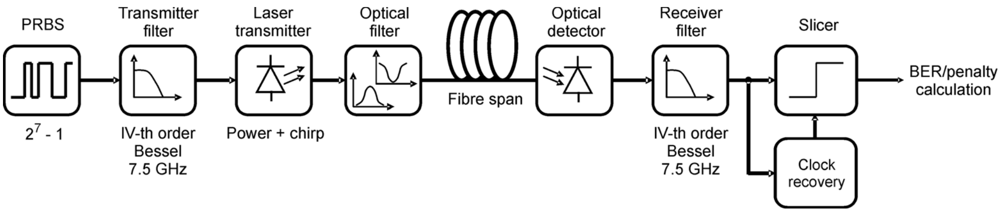

Fig. 3. Block diagram of the simulation setup.

The performance of the digital link is described using the so-called power (or sensitivity) penalty. This is regarded as the increase in the transmitter power (or the sensitivity of the receiver) required to restore some certain bit error rate (typically 10^{-12}) in the link where the signal is deformed (*e.g.*, by dispersion). It is also assumed that the main cause of errors is the additive white noise described by Gaussian probability distribution. In calculating the penalty, full extinction of the laser during transmission of the 0 level (*i.e.*, infinite extinction ratio ER = ∞) was taken as the reference. Although some reasons exist to operate DMLs with lower ER values in the range of 3 – 10 dB [28] resulting in an additional increase, the penalty is not greater than 1.2 dB if ER ≥ 6 dB.

4. Optimisation of the characteristics of the filter

Optimisation of the fibre link with the optical filter is a multivariable one. It requires searching for the best values of the detuning Δf of the central wavelength of the DML from the –3 dB filter point, the roll-off of the filter *S*, its bandwidth *B* and also the extinction ratio of the DML. Basing on the initial observations, we decided to set values of some parameters of lower importance constant to get the results that are easier to interpret. After finding the optimal values of the first-order parameters, the other ones were also varied to check their influence on the power penalty. Thus, it was assumed that ER = 6 dB would be taken. This is because lower values of ER result in too high extinction penalty and higher values of ER lead to excessive signal distortions because of dispersion. It was also observed that the bandwidth *B* in the order of 10 GHz seems to be a reasonable choice.

Thus, the optimal values of the roll-off and the location of the DML central wavelength on the filter slope were searched first. The results for the band-pass filter (Eq. (3)) are presented in Fig. 4. On the abscissa, the DML detuning Δf from the filter –3 dB point is marked, whereas on the ordinate, the roll-off *S*, also calculated in the –3 dB point, is marked. In Figure 4**a** the contours are drawn for the accumulated dispersion equal to 600 ps/nm (~35 km of standard SMF). In Figure 4**b** the total dispersion is 1700 ps/nm (~100 km of standard SMF). Basing on presented graphs, it may be noted that the optimal values of Δf and *S* display some dependence on the transmission distance. However, because the regions of low penalty are quite broad and partially overlapping, the values of the DML detuning and tilt of the filter slope

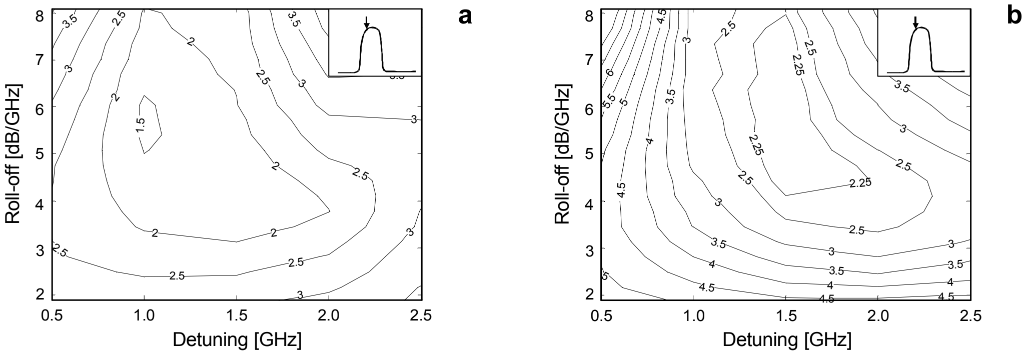

Fig. 4. Contours of constant penalty for accumulated dispersion equal to 600 ps/nm (**a**) and 1700 ps/nm (**b**) for the band-pass filter (insets show localization of the laser central frequency).

about 1.4 GHz and 5.5 dB/GHz, respectively, may be regarded as a joint "optimum", from the practical point of view.

To check how the extinction ratio affects the performance of the link, the graphs of the penalty plotted versus the accumulated dispersion for a few different values of ER are presented in Fig. 5**a**. The values of detuning and roll-off given above were used. The tolerance to the change of the ER appears to be quite high as the curves are located very closely each other. This confirms the initial choice of ER = 6 dB as correct.

However, the penalty is more sensitive to the bandwidth of the optical filter. This is presented in Fig. 5**b**. It may be observed that for the accumulated dispersion lower than about 2000 ps/nm (~120 km) the filter with the bandwidth equal to 10 GHz gives reasonably low values of the penalty (below 2.4 dB). For short links with low accumulated dispersion (below about 500 ps/nm) even wider filter performs better, but the possible gain (in comparison with the filter with bandwidth B = 10 GHz) is not very high, being not greater than about 0.6 dB. On the other hand, for high values of

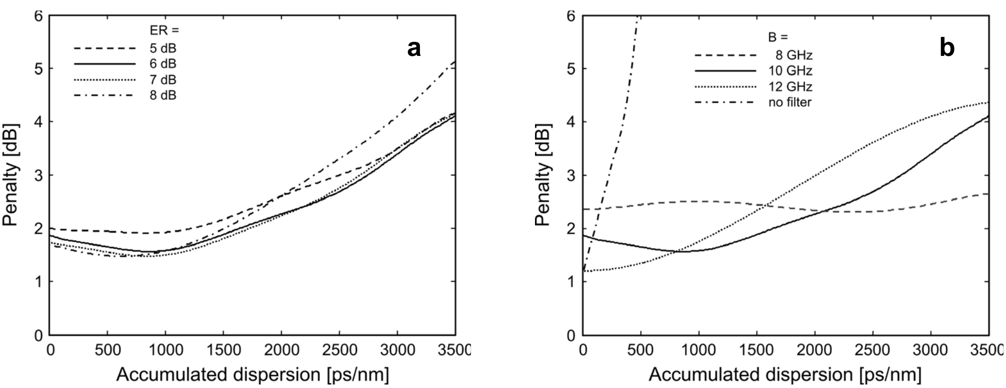

Fig. 5. Influence of the extinction ratio (**a**) and bandwidth (**b**) on the penalty for the band-pass filter.

total dispersion (more than about 2000 ps/nm), lowering the bandwidth of the filter is beneficial. This time the gain appears to be quite substantial, and for the filter with $B_0 = 8$ GHz it is about 1.5 dB at total dispersion 3400 ps/nm (~200 km). (In above calculations the detuning equal to 1.4 GHz and the roll-off 5.5 dB/GHz were used for the filter with $B = 10$ GHz. For two other filters, those parameters were $\Delta f = 1.4$ GHz, $S = 5.5$ dB/GHz for $B = 8$ GHz and $\Delta f = 1.5$ GHz, $S = 4.6$ dB/GHz for $B = 12$ GHz, respectively. They were optimised to get the lowest penalty for short and long links, respectively.)

It is worth mentioning here that, without the filter into the optical path, the penalty increases very fast with the accumulated dispersion. The curve for this case is also shown in Fig. 5**b** for the reference. The accumulated dispersion as low as about 500 ps/nm (~35 km of standard SMF) results in the penalty exceeding 6 dB. Such high value is hardly acceptable in practice. On the other hand, applying properly designed filter enables the transmission distance in the range over 200 km with about 2.6 dB penalty, with 1.2 dB originating from limited ER. (Such long-distance spans require of course some kind of optical amplification to compensate for the attenuation of the fibre.)

The performance of the fibre link with the band-stop filter accordingly to Eq. (4) will be discussed next. In Figure 6 the maps are presented showing the penalty in the laser detuning – filter tilt coordinates. Similarly to the band-pass filter case, the maps are calculated for the accumulated dispersion equal to 600 ps/nm (Fig. 6**a**) and 1700 ps/nm (Fig. 6**b**) and assuming $B = 10$ GHz. It may be noticed that the optimal value of the detuning now is $\Delta f = 1.5$ GHz. For the roll-off, some slight dependence on the accumulated dispersion is noticeable, however the areas of constant penalty are quite broad. Thus, the common value of the optimum roll-off of about 5 dB/GHz may be assumed. In comparison with the band-pass filter case, somehow higher values of the penalty are observed now, especially for longer transmission spans (Fig. 4**b** *vs.* Fig. 6**b**).

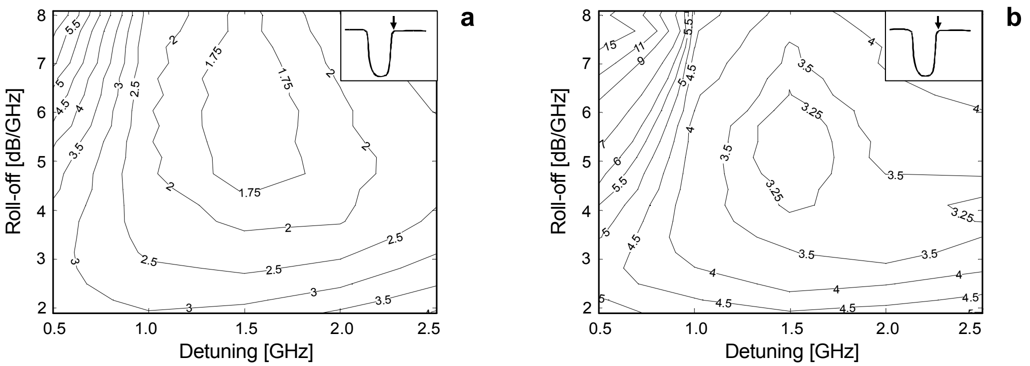

Fig. 6. Contours of constant penalty for accumulated dispersion equal to 600 ps/nm (**a**) and 1700 ps/nm (**b**) for the band-stop filter (insets show localization of the laser central frequency).

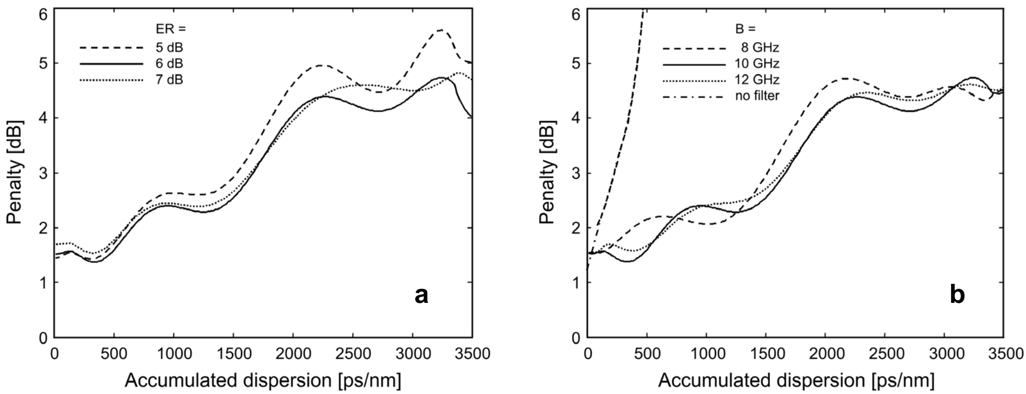

Fig. 7. Influence of the extinction ratio (**a**) and bandwidth (**b**) on the penalty for the band-stop filter.

In Figure 7**a** the dependence of the penalty on the accumulated dispersion of the fibre is shown. As previously, the curves are plotted for a few values of the ER, taking $B = 10$ GHz, $\Delta f = 1.5$ GHz and $S = 5$ dB/GHz. From the plot it is evident that ER = 6 dB is a reasonable choice and slight departure from this value has minor effect. The result of varying the filter bandwidth is shown in Fig. 7**b**. It appears however, that for the band-stop optical filter there is no substantial effect on the penalty. Even searching for the optimal values of the roll-off and detuning gives only minor improvement. Nevertheless, the values used to prepare Fig. 7**b** were optimised to get the best result for the longest transmission spans.

The different behavior of the band-pass and band-stop filters is not surprising however. In the case of the band-pass filter, the main part of the optical spectrum is passed through the filter (*i.e.*, is located in its pass-band). Thus changing the bandwidth of the filter affects the amount of higher frequency components entering the fibre. This is different in the case of the band-stop filter. Here the higher-frequency components of the spectrum are almost not affected by the filter, whereas the lower-frequency part of the spectrum is highly attenuated, regardless of the filter bandwidth.

Comparing the plots presented in Fig. 7**b** to those in Fig. 5**b**, it may be observed that for low values of the accumulated dispersion (about 1000 ps/nm; ~60 km) both band-pass and band-stop filters offer similar improvement of the link performance. For longer transmission spans, however, the band-pass filter performs much better.

The question arises about the sensitivity of the method discussed herein to the change in the chirping parameters of the laser. It was checked that varying α and κ about $\pm 10-15\%$ (from values quoted in Section 3) does not influence much the penalty, reducing it by a fraction of dB only. Larger changes are disadvantageous, however, and require matching another filter to get the desired performance.

Because of that, the optimisation of the filters was also performed for other DMLs with chirping parameters substantially different from those initially assumed (either measured or known from the literature). General trends observed for the NLK1551SSC laser are also true for other DMLs: band-pass filters perform better than band-stop ones and filters with lower bandwidth are better for longer transmission spans. Presented method works well when the adiabatic component of the chirp is around 2−7 GHz with comparable amount of the dynamic component. For highly chirped signals, the gain resulting from the filtering decreases. Some relation also exists among the bandwidth of the filter, its roll-off and the amount of adiabatic chirp. Generally, a larger chirp (*i.e.*, greater values of α, κ and ER) requires a wider bandwidth and less roll-off, no simple rule of thumb was found however. For adiabatic chirp greater than about 8 GHz, the best results are obtained using relatively wideband filter, where only the rising slope of the filter effectively affects the signal.

As an example, the optimisation of the band-pass filter for the laser NLK5C5E2KA, rated at 10 Gbit/s and manufactured by NEL, is presented. The chirping parameters (obtained from [6]) for this DML are $\alpha = 3.5$ and $\kappa = 6.5$ GHz/mW. It was found that the optimum bandwidth of the filter is $B = 12$ GHz in this case. Also reducing the ER from 6 dB to 5 dB appears to be advantageous a bit and results in broadening the region of low value of the penalty. The resulting map of the penalty for the accumulated dispersion of 1200 ps/nm (about 75 km of standard SMF) is presented in Fig. 8**a**. The optimal values of detuning and roll-off are almost the same as it was for NLK1551SSC and are $\Delta f = 1.4$ GHz and $S = 5$ dB/GHz. In Figure 8**b** the eye diagrams calculated at the end of the link are shown.

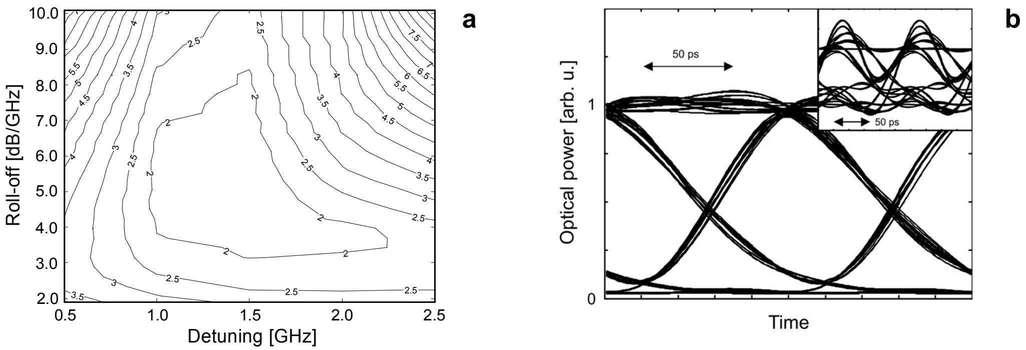

Fig. 8. Optimisation of the filter for NLK5C5E2KA laser: constant penalty contours for 1200 ps/nm of total dispersion (**a**), eye diagram with the filter (**b**); diagram without the filter in the inset.

It is worth mentioning that different types of the characteristics of the filter also result in similar improvement of the penalty. The authors successfully tried some standard filter types, like Butterworth, Bessel−Thompson and Chebyshev filters. If the values of roll-off and offset were the same, the impact on the eye diagram was very similar in each case. Even using the hyperbolic tangent function to model the rising slope of the filter with the phase characteristic obtained from the Kramers−Kronig relation was successful. This observation reveals the fact that the improvement described herein is of quite general nature, not strictly connected with some particular type of the filter.

5. Experimental results

To prove the theoretical investigations presented in the above sections, some experiments were performed. As the filter standard DWDM fibre Bragg grating operating in transmission was used. Measured amplitude and group delay of the filter are presented in Fig. 9. The bandwidth of this filter is $B = 12.23$ GHz (about 0.1 nm) and the roll-off is $S = 3.35$ dB/GHz. Together with the measured characteristics, the approximations used in simulations are also displayed with the dashed lines. The only modification with relation to Eq. (4) was limiting the maximum attenuation to 21 dB to make the approximation closer to the real characteristic. According to the results presented in Section 4, the roll-off of this Bragg grating is not the optimal one and is about 70% of what would be necessary. Nevertheless, this filter should perform quite well – detailed calculations show that the penalty in the order of 2.5 dB and 3.5 dB for accumulated dispersion of 600 ps/nm and 1700 ps/nm, respectively, might be expected.

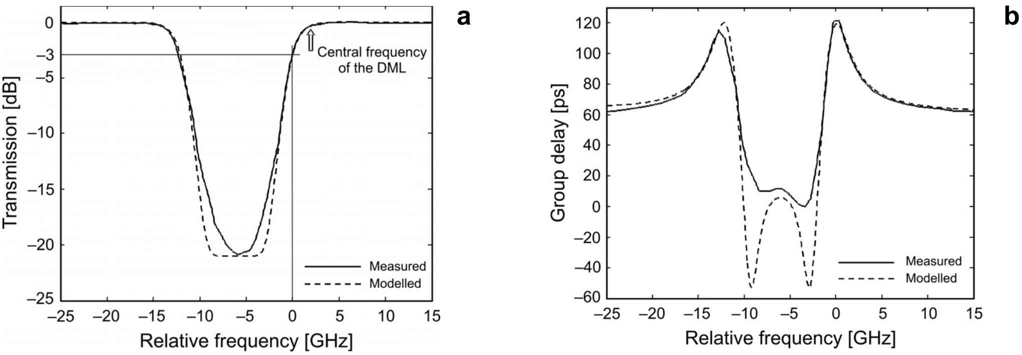

Fig. 9. Attenuation (**a**) and group delay (**b**) of the filter used in the experiment.

The measurement setup used in the hardware experiment is shown in Figure 10. The signal was registered with HP83480A mainframe, equipped with HP83494A clock-recovery and HP83485B opto-electrical plug-ins. The electrical bandwidth was limited to ~7.5 GHz using internal filter available in HP83485B. The NLK1551SSC

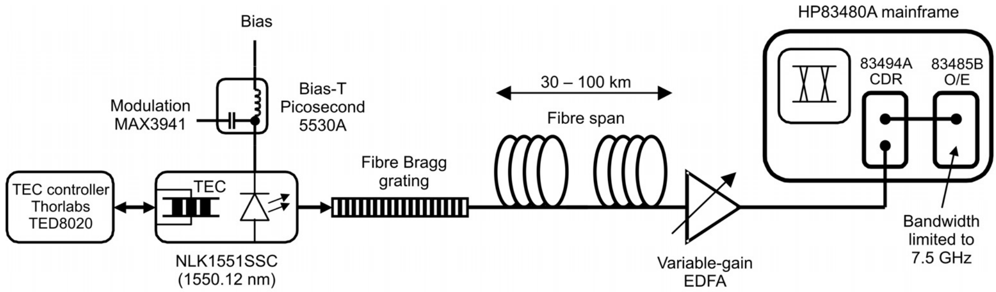

Fig. 10. Diagram of the measurement setup.

laser modulated with 2^7-1 pseudo-random signal running at 10 Gbit/s was used. The high power level at the laser output was about 4 mW and the ER was about 5.4 dB. The central wavelength of the laser was offset about 1.55 GHz form the point of 3 dB attenuation of the filter, what is very close to the optimum value accordingly to Fig. 6. Central wavelength of the DML was controlled by controlling its temperature. In each case the erbium-doped fibre amplifier (EDFA) was used to compensate for the attenuation of the fibre. The gain of the amplifier was adjusted to get visually comparable waveforms.

In Figure 11 the improvement of the eye diagram resulting from applied optical filtering is presented. The measurements were performed for the transmission distance equal to 35 km, 60 km and 100 km of standard SMF, what corresponds to the accumulated dispersion of 600 ps/nm, 1000 ps/nm and 1700 ps/nm, respectively. The first column shows the eye diagrams measured at the output of the fibre without the filter, whereas the second one was obtained with the filter. It is observed that, quite independently of the length of the link, passing the signal from the DML through the Bragg grating results in spectacular improvement of the eye diagram. The eye diagrams simulated basing on the model of the band-stop filter, with the bandwidth and roll-off extracted from the measured characteristics of the Bragg grating, are shown in the last two columns in Fig. 11. These are in good agreement with the diagrams obtained from the measurement. This may be regarded as the proof of the models and methods used to perform the calculations. Some small differences between measured and simulated diagrams may result from slight differences between the measured and

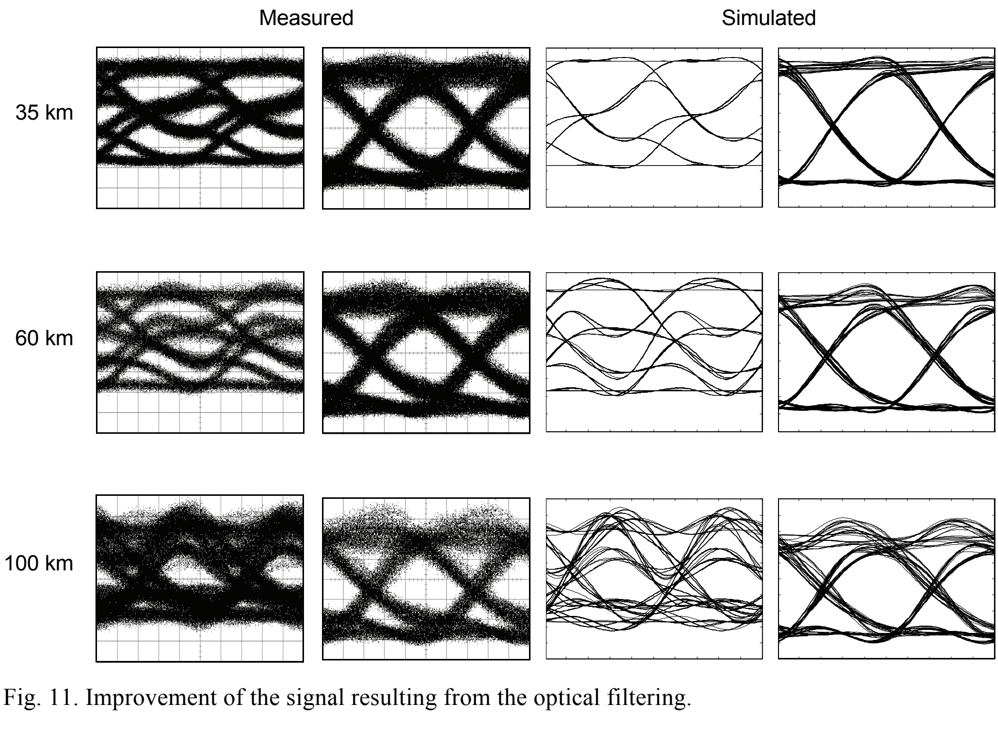

Fig. 11. Improvement of the signal resulting from the optical filtering.

modelled characteristics of the optical filter (see Fig. 9) and from simple linear modelling of the DML dynamics used in the simulations.

6. Conclusions

When using directly modulated lasers, the transmission distance at 10 Gbit/s is limited because of laser chirp and fibre dispersion. Typically, the transmission span is not greater than about 20 km of the standard SMF. Optical filtering based on passing the chirped signal from the DML through the filter with high roll-off allows tolerating a substantial amount of the dispersion, pushing the transmission distance around 100 km.

In the paper, the calculations were performed for the NLK1551SSC (1550.12 nm) laser with the line enhancement factor $\alpha = 1.8$ and the adiabatic chirp coefficient $\kappa = 6.3$ GHz/mW. The central wavelength of the laser should be positioned on the rising slope of the filter with the offset around 1.5 GHz relative to the 3 dB attenuation point. Using the band-pass filter, the penalty better than 2.5 dB may be obtained for bandwidth $B = 8-12$ GHz and roll-off $S = 3.5-8$ dB/GHz. Required accuracy of the central wavelength of laser is about ±400 MHz. Somewhat worse results may be obtained using a band-stop filter. In this case, the penalty below 3.5 dB may be obtained for similar values of S and detuning as for the band-pass filter, whereas the bandwidth B, as it appears, does not influence much the results. For either filter, the extinction of the laser should be about 5−6 dB, with no requirement of precise control. Careful adjustment of the parameters of the filter makes it possible to accept even more dispersion: *e.g.*, the band-pass filter with $B = 8$ GHz and $S = 5.5$ dB/GHz works well for accumulated dispersion over 3400 ps/nm (more than about 200 km of standard SMF), with the penalty not worse than ~2.6 dB.

Changing the chirping parameters of the laser generally affects the parameters of the filter required to get the best results. No simple rules were found linking these parameters with the parameters of the DML. The most important factor influencing the design of the filter is the relation between the adiabatic chirp and the dynamic one. Thus, numerical methods must be used to find optimal filter for the particular laser type.

For the method of extending the reach of the DML transmitters described herein, the precise control of the laser wavelength relative to the characteristic of the optical filter is essential. This, however, may be performed using standard wavelength--stabilization scheme based on Fabry−Perot etalon and routinely used in DWDM systems. The only difference in discussed case is that now the optical filter used for shaping the optical signal must serve as the etalon as well. This point is crucial as the characteristic of the filter slightly shifts with the temperature, what, in case of using external wavelength reference, will result in degradation of the overall performance. In this context, the method described in [22], based on fine offsetting of the DML wavelength relative to the characteristics of the filters working as the demultiplexers in DWDM system, might be rather cumbersome.

It should be emphasized that the optical filter placed at the output of the DML shapes the chirp waveform relatively to the instantaneous optical power at the input to the fibre, thus resulting effects are highly independent of the transmission distance. Therefore, the transmitter equipped with the filter is able to tolerate dispersion starting from its zero value. This is substantially different from various dispersion compensating schemes that must be adjusted to the transmission span. Furthermore, the dispersion compensating devices (either based on special fibres or Gires–Tournois etalons) introduce substantial insertion loss. On the other hand, the optical filter, especially manufactured as TFF, may be quite small and even integrated in one package with the DML. Moreover, because the discussed method is not designed for some peculiar dispersion, its operation is not contradictory with using any form of standard dispersion compensators.

Theoretical results presented in this paper were verified experimentally using standard fibre Bragg grating operating in the transmission and NLK1551SSC DML running at 10 Gbit/s. The results of the experiments are in good agreement with the theoretical predictions. Thus, it may be concluded that applied methods and models are appropriate for optimising the parameters of the filters increasing the dispersion tolerance of directly modulated lasers.

References

[1] SACKINGER E., *Broadband Circuits for Optical Fiber Communication*, Wiley, Hoboken, 2005.

[2] MOHRIDEK S., BURKHARD H., STEINHAGEN F., HILLMER H., LOSH R., SCHLAPP W., GOBEL R., *10 Gb/s standard fiber transmission using directly modulated 1.55-μm quantum-well DFB lasers*, IEEE Photonics Technology Letters **7**(11), 1995, pp. 1357–1359.

[3] SOGAWA I., KAIDA N., IWAI K., TAKAGI T., NAKABAYASHI T., SASAKI G., *Study on full spectrum directly modulated 10 Gb/s per channel CWDM transmission*, SEI Technical Review, No. 56, 2003, pp. 31–36.

[4] KREHLIK P., *Directly modulated lasers in negative dispersion fiber links*, Opto-Electronics Review **15**(2), 2007, pp. 71–77.

[5] HUISZOON B., JONKER R.J.W., VAN BENNEKOM P.K., KHOE G.-D., DE WAARDT H., *Cost-effective up to 40 Gb/s transmission performance of 1310 nm directly modulated lasers for short-to medium--range distances*, Journal of Lightwave Technology **23**(3), 2005, pp. 1116–1125.

[6] SATO K., KUWAHARA S., MIYAMOTO Y., *Chirp characteristics of 40-Gb/s directly modulated distributed-feedback laser diodes*, Journal of Lightwave Technology **23**(11), 2005, pp. 3790–3797.

[7] COLDREN L., CORZINE S., *Diode Lasers and Photonic Integrated Circuits*, Wiley, New York, 1995.

[8] YARIV A., YEH P., *Photonics*, Oxford University Press, Oxford, 2007.

[9] NIEMI T., TAMMELA S., LUDVIGSEN H., *Device for frequency chirp measurements of optical transmitters in real time*, Review of Scientific Instruments **73**(3), 2002, pp. 1103–1107.

[10] LAVERDIERE C., FEKECS A., TETU M., *A new method for measuring time-resolved frequency chirp of high bit rate sources*, IEEE Photonics Technology Letters **15**(3), 2003, pp. 446–448.

[11] KREHLIK P., *Characterization of semiconductor laser frequency chirp based on signal distortion in dispersive optical fiber*, Opto-Electronics Review **14**(2), 2006, pp. 119–124.

[12] GNAUCK A., JOPSON R., *Dispersion compensation for optical fiber systems*, [In] *Optical Fiber Telecommunications IIIa*, [Eds.] Kaminov I., Koch T., Academic Press, 1997.

[13] WINZER P.J., FIDLER F., MATTHEWS M.J., NELSON L.E., THIELE H.J., SINSKY J.H., CHANDRASEKHAR S., WINTER M., CASTAGNOZZI D., STULZ L.W., BUHL L.L., *10-Gb/s upgrade of bidirectional CWDM systems using electronic equalization and FEC*, Journal of Lightwave Technology **23**(1), 2005, pp. 203–210.

[14] BINDER J., KOHN U., *10 Gbit/s-dispersion optimized transmission at 1.55 μm wavelength on standard single mode fiber*, IEEE Photonics Technology Letters **6**(4), 1994, pp. 558–560.

[15] MORTON P.A., SHTENGEL G.E., TZENG L.D., YADVISH R.D., TANBUN-EK T., LOGAN R.A., *38.5 km error free transmission at 10 Gbit/s in standard fibre using a low chirp, spectrally filtered, directly modulated 1.55 μm DFB laser*, Electronics Letters **33**(4), 1997, pp. 310–311.

[16] YAN L.-S., WANG Y., ZHANG B., YU C., MCGEEHAN J., PARASCHIS L., WILLNER A.E., *Reach extension in 10 Gb/s directly modulated transmission systems using asymmetric and narrowband optical filtering*, Optics Express **13**(13), 2005, pp. 5106–5115.

[17] CHANG-HEE LEE, SANG-SOO LEE, HYANG KYUN KIM, JUNG-HEE HAN, *Transmission of directly modulated 2.5-Gb/s signals over 250 km of nondispersion-shifted fiber by using a spectral filtering method*, IEEE Photonics Technology Letters **8**(12), 1996, pp. 1725–1727.

[18] SUNG-BUM PARK, CHANG-HEE LEE, *Enhancement of system performance in directly modulated metro-WDM systems by a spectral filtering method*, Electronics Letters **38**(9), 2002, pp. 418–419.

[19] MAHGEREFTEH D., LIAO C., ZHENG X., MATSUI Y., JOHNSON B., WALKER D., FAN Z.F., MCCALLION K., TAYEBATI P., *Error-free 250 km transmission in standard fibre using compact 10 Gbit/s chirp-managed directly modulated laser (CML) at 1550 nm*, Electronics Letters **41**(9), 2005, pp. 543–544.

[20] MATSUI Y., MAHGEREFTEH D., XUEYAN ZHENG, LIAO C., FAN Z.F., MCCALLION K., TAYEBATI P., *Chirp-managed directly modulated laser (CML)*, IEEE Photonics Technology Letters **18**(2), 2006, pp. 385–387.

[21] EGGLETON B.J., STEPHENS T., KRUG P.A., DHOSI G., BRODZELI Z., OUELLETTE F., *Dispersion compensation using fibre grating in transmission*, Electronics Letters **32**(17), 1996, pp. 1610–1611.

[22] DOWNIE J., VODHANEL R., *Optical demultiplexer filtering to increase the uncompensated reach of 10-Gbit/s directly modulated lasers*, Journal of Optical Networking **4**(5), 2005, pp. 248–259.

[23] PAPAGINNAKIS A., KLONIDIS D., KIKIDIS J., BIRBAS A., TOMKOS I., *Transmission performance improvement studies for low-cost 2.5 Gb/s rated DML sources operated at 10 Gb/s*, 34th European Conference on Optical Communication ECOC, Brussels, 2008, paper Tu.1.D.5.

[24] ŚLIWCZYŃSKI Ł., KREHLIK P., *Increasing dispersion tolerance of 10 Gbit/s directly modulated lasers using optical filtering*, AEÜ – International Journal of Electronics and Communications, DOI 10.1016/j.aeue.2009.02.004 (in press).

[25] LENZ G., EGGLETON B.J., GILES C.R., MADSEN C.K., SLUSHER R.E., *Dispersive properties of optical filters for WDM systems*, IEEE Journal of Quantum Electronics **34**(8), 1998, pp. 1390–1402.

[26] SALEH B., TEICH M., *Fundamentals of Photonics*, Wiley, New Jersey, 2008.

[27] ŚLIWCZYŃSKI Ł., *Resolving group delay of narrowband optical filters from their transmission characteristics*, Opto-Electronics Review **17**(4), 2009, pp. 318–324, DOI 10.2478/s11772-009-0003-1.

[28] KREHLIK P., *Directly modulated lasers in chromatic dispersion limited 10 Gb/s links*, Electronics and Telecommunications Quarterly **53**(2), 2007, pp. 177–191.

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