

# Time domain all-optical signal processing at a RZ optical receiver

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**Abstract:** We propose a new all-optical signal processing technique to enhance the performance of a return-to-zero optical receiver, which is based on nonlinear temporal pulse broadening and flattening in a normal dispersion fiber and subsequent slicing of the pulse temporal waveform. The potential of the method is demonstrated by application to timing jitter- and noise-limited transmission at 40 Gbit/s.

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## 1. Introduction

In high-speed optical fiber communication systems using return-to-zero (RZ) modulation format, an optical bandpass filter (OBPF) and an electrical low-pass filter (ELPF) are normally employed at the optical receiver before and after direct detection, respectively. The OBPF filters the incoming optical signal, removing the accumulated out-of band amplified spontaneous emission (ASE) noise generated by in-line amplifier repeaters at the detector. The ELPF shapes the voltage signal. It has two functions. One is that the filter limits the receiver bandwidth in order to further reduce the noise both accumulated during the transmission stage and generated in the receiver. The other one is that the filter expands the pulse width provided that the duty ratio of the received pulse is sufficiently small and, therefore, reduces the influence of the fluctuation of pulse position in time caused by timing jitter [1]. However, there exists a trade-off

in the cut-off frequency of the electrical filter among the effects of intersymbol interference (ISI), signal amplitude reduction, and signal-to-noise ratio (SNR) improvement. Recently, the use of Kerr nonlinearity in a normal dispersion fiber (NDF) has been introduced as a technique to reduce the impact of timing jitter at a RZ receiver [2, 3]. A nonlinear pulse processor for use at a RZ receiver, which combines the intensity filtering action of a nonlinear optical loop mirror (NOLM) for signal reamplification and cleaning up with the Kerr effect in a NDF for phase margin improvement, has been studied in [4].

In this paper, we propose a novel scheme of all-optical nonlinear signal processing for application to a RZ optical receiver, which relies on shaping of the optical pulses in the time domain. Specifically, the proposed method is based on nonlinear temporal pulse broadening and flattening in a NDF and subsequent slicing of the pulse temporal waveform by a modified synchronous amplitude modulator (AM) or any other device that can perform this function. The technique is applied to timing jitter- and noise-limited RZ transmission at 40 Gbit/s. Substantial suppression of the timing jitter of the signals and overall improvement of the receiver performance is demonstrated by the proposed approach.

## 2. Operation principle and configuration

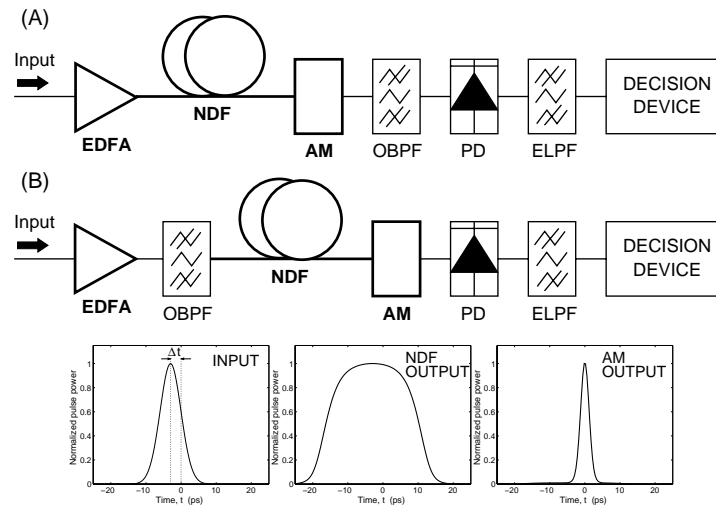


Fig. 1. Schemes of the proposed RZ optical receiver.

The schematic diagram of the proposed nonlinear pulse processor-enhanced receiver is depicted in Fig. 1. The receiver is constructed by an OBPF, a photodiode with a square-law detection characteristic, an ELPF, and a decision circuit. The pulse processor, placed before the detector, consists of an erbium-doped fiber amplifier (EDFA), a section of NDF, and an AM. Two configurations are used: configuration (A) where the OBPF follows the AM, and configuration (B) where the OBPF is located immediately after the EDFA.

Qualitatively, the idea for the method is as follows. An input optical pulse to the pulse processor is first amplified by the optical amplifier in order to enhance the effect of nonlinearity in the NDF. During transmission along the NDF, the temporal waveform of the pulse is changed to a rectangular-like profile by the combined action of group-velocity dispersion and Kerr nonlinearity [5, 6]. As a result, the pulse width is broadened and the center portion of the pulse changes to be flat. By utilizing this property in order to broaden the pulse width properly, the phase margin of a RZ pulse train is improved [2, 3]. This reduces the influence of the displace-

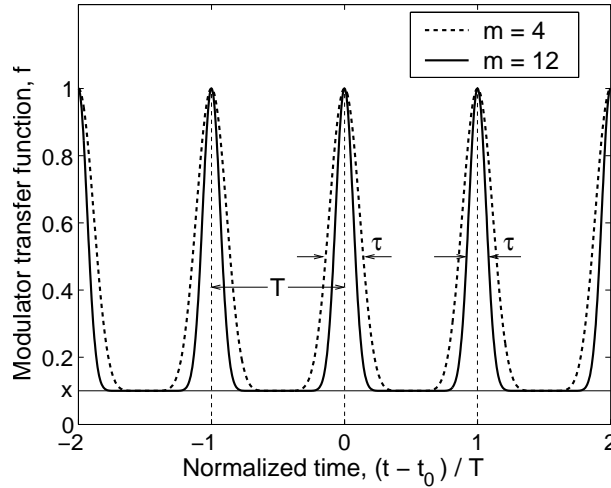


Fig. 2. Amplitude modulator transfer function.

ment of pulse position in time caused by timing jitter. Indeed, broadening of the pulse width to approximately a bit duration causes the center of mass of the pulse portion contained in the bit slot to move towards the pulse top, where timing jitter is less than in the tails as a result of flattening of the pulse envelope. Following the NDF, the pulse enters the AM. The AM re-times the pulse and acts as an optical gate in slicing the center portion of the broadened pulse temporal profile. This effective discrimination of the pulse tails against the center portion enables efficient suppression of the timing jitter of a pulse train. The pulse shape and width of the output pulse from the AM are determined by the AM transfer function (see Fig. 1). In order to enhance the optical gating effect of the AM, without loss of generality, we propose here a particular example of nonlinear transfer function given by

$$f(t) = x + (1 - x) \cos^{2m} \left( \frac{\pi(t - t_0)}{T} \right), \quad m = 1, 2, \dots \quad (1)$$

In Eq. (1),  $1 - x$  defines the modulation depth,  $t_0$  is the center of the modulation,  $T$  is the bit period, and parameter  $m$  controls the degree of narrowing and sharpening of the peaks of the modulation (see Fig. 2) and, thus, the degree of slicing of the pulse temporal profile. We would like to stress that even though a modified nonlinear transfer function for the AM could be realized in practice, here Eq. (1) is only a particular example of such a narrow response function, and obviously, other devices (already known and to be developed) with linear or nonlinear transfer functions may be used for temporal gating/slicing. As an example, a NOLM provided with a clock could be used for this purpose. Such a gate would provide a different nonlinear transfer function from the one in Eq. (1), but would have the same essential properties of  $f$  in that it would open a narrow window in time  $\tau$  with periodicity  $T$ .

In the exemplary system used for demonstration of the technique, the EDFA has a noise figure of 4.5 dB. The NDF is 0.5 km long, and has a dispersion of  $-20 \text{ ps}/(\text{nm km})$ , a nonlinear coefficient of  $4.28 (\text{W km})^{-1}$ , and an attenuation of 0.24 dB/km. A Gaussian filter is used as a receiver OBPF, and a fifth-order Bessel filter is used as a receiver ELPF.

### 3. Modelling results

To illustrate the operation of the proposed pulse processor-enhanced receiver, without loss of generality, the following model simulations are run. Transmitted are 40 Gbit/s pseudorandom

RZ single-channel pulse trains of bit length  $N = 1024$  in two different types of systems: a system whose transmission performance is severely limited by timing jitter [7], and a system dominated by accumulation of noise. Note that we focus here on the high-frequency timing jitter mainly induced by nonlinear pulse-to-pulse interactions and amplifier noise during the transmission stage. We neglect the low-frequency timing jitter such as that generated by thermal fluctuations in the system because we assume that this timing jitter will be tracked by a clock-recovery circuit at the receiver. The transmitted pulses are detected with the proposed method or the conventional scheme. The signal quality is evaluated in terms of the standard (Gaussian-based)  $Q$ -factor. We note that the  $Q$ -factor is used here as a measure of the opening of the signal eye rather than a measure of the bit-error rate. In other words, the  $Q$ -factor is used as a characteristic of both the changes in the probability density function and the signal phase margin improvement. The  $Q$ -factors are obtained by averaging a set of four simulations and, unless otherwise specified, are calculated at the sampling time for which the sum of the bit amplitudes is maximal.

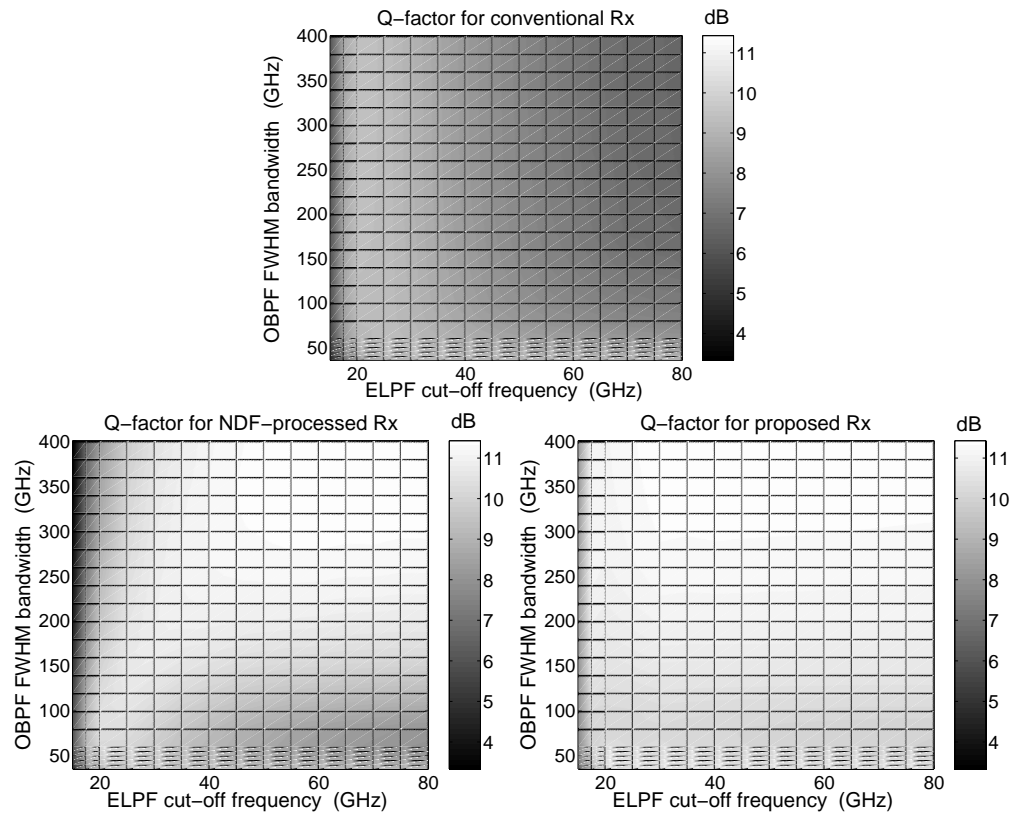


Fig. 3.  $Q$ -factor versus cut-off frequency of the electrical filter and bandwidth of the optical filter for timing jitter-limited transmission. Top, conventional receiver; bottom, NDF-processed receiver (left) and proposed pulse processor-enhanced receiver (right).

The improvement of signal quality that can be achieved in the nonlinear pulse processor-modified receiver with respect to the conventional receiver is evident from Fig. 3, where the signal  $Q$ -factor is plotted as a function of the cut-off frequency of the ELPF and the full-width at half-maximum (FWHM) bandwidth of the OBPF for the two receiver types, when the receiver is applied to timing jitter-degraded signals. In this case, the location of the OBPF does

not really matter, and configuration (A) is used for the modified receiver as an example. For comparison, the performance of the signal processed receiver without AM [2, 3] is also illustrated. In the example of Fig. 3, the input pulses to the receiver have a FWHM pulse width of approximately 7 ps (corresponding to a duty cycle of 28%), the gain of the EDFA is 34.2 dB, and transfer function (1) is used for the AM with  $x = 0.1$  and  $m = 12$ . It is seen that when timing jitter is the main factor of deterioration of the signal, the receiver optical bandwidth has a small impact on the receiver performance, and the performance is mainly determined by the receiver electrical bandwidth. This result is evident since in the selected example there is no appreciable optical bandwidth dependent noise in the signal. Clearly, the only effect of the OBPF in such a case is to degrade the performance (via ISI) if its bandwidth is narrower than the signal bandwidth. For the conventional receiver, when the cut-off frequency of the ELPF is too low, the signal quality is degraded by the increase of ISI and the decrease of pulse amplitude. Large cut-off frequency leads to a decrease of the SNR in the detected electrical signals, and this also results in degradation of the signal quality. At the optimum cut-off frequency of 20 GHz, the  $Q$ -factor does not vary appreciably with the optical filter bandwidth, although optimum performance is achieved here with an optical FWHM bandwidth of 400 GHz. Small bandwidths of the OBPF can help to improve the SNR when the electrical cut-off frequency is large. The trivial dependence of the receiver performance on the optical bandwidth for the conventional receiver is shown here only for comparison with the proposed technique. When the receiver is enhanced by the NDF-based or the proposed pulse processor, the nonlinear pulse broadening in the NDF permits to improve the signal phase margin without increasing the ISI. In the NDF-enhanced and the proposed scheme, the required electrical bandwidth is wider than that of the conventional receiver since also the pulse spectrum spreads out. However, because of the nonlinearity involved in the process, the SNR is not significantly decreased for a wide range of cut-off frequencies. It is seen that the NDF-enhanced scheme sensibly widens the tolerable margins of the receiver filter parameters. The estimated  $Q$ -factor is improved by 0.5 dB or more compared to the optimum  $Q$  for the conventional receiver within a large region of filter parameters, which is lower down delimited by electrical cut-off frequencies of the order of 30 GHz and optical FWHM bandwidths of the order of 120 GHz. Optimum performance is achieved here with an electrical cut-off frequency of 70 GHz and an optical FWHM bandwidth of 400 GHz, yielding a  $Q$ -factor improvement of 1.9 dB over the conventional receiver. The proposed scheme widens the tolerance of the receiver filter parameters further. The estimated  $Q$ -factor is improved by 0.5 dB or more compared to the optimized conventional receiver within the whole considered parameter region with the exception of electrical cut-off frequencies less than 17.5 GHz. Optimum performance is achieved with an electrical cut-off frequency of 40 GHz and an optical FWHM bandwidth of 400 GHz, yielding a  $Q$ -factor improvement of 1.9 dB over the conventional receiver. Figure 4 shows an example of eye-diagrams of the optical signal at the input to the receiver, and of the detected electrical signal in the conventional, the NDF-processed, and the proposed receiver. In this example, the optimum optical and electrical filter parameters are used for each of the receiver types. The eyes are generated from a single pulse train. It can be seen that the optical input eye is closed mainly due to a significant timing jitter of the pulses. When the pulses are detected with the conventional scheme, the pulse width is broadened by the ELPF, and this results in increase of the eye opening. Dispersion and nonlinearity in the NDF broaden the pulse duration and simultaneously flatten the pulse shape. In Fig. 4, the FWHM pulse width is broadened to approximately a bit duration. Consequently, the eye-opening detected with the NDF-enhanced scheme is larger than that in the conventional receiver. The eye-opening detected with the proposed scheme is larger still. This is due to a substantial suppression of the timing jitter, which results from the temporal slicing of the NDF-broadened and flattened pulse waveforms by the AM. Note that in the proposed scheme, the optical pulses at

the pulse processor output exhibit sharper edges and mostly a narrower width than at the input. In the example of Fig. 4, the output FWHM pulse width is approximately 3 ps.

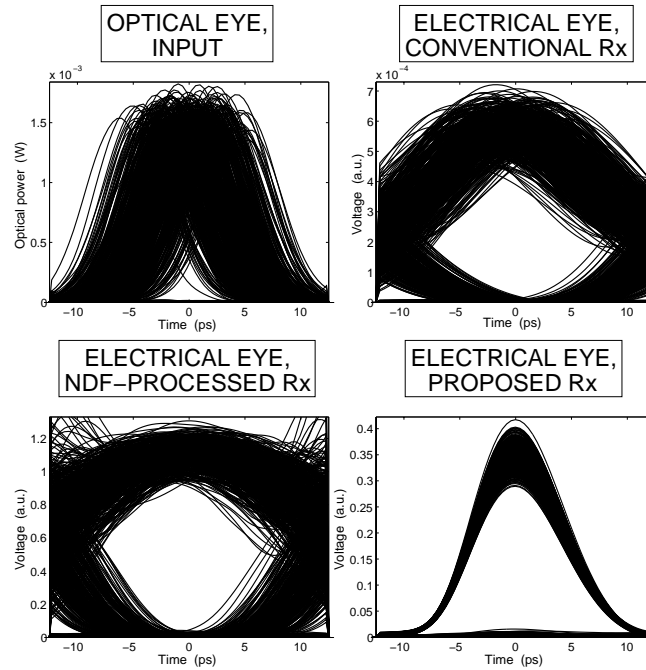


Fig. 4. Eye-diagrams in the receiver for timing jitter-limited transmission.

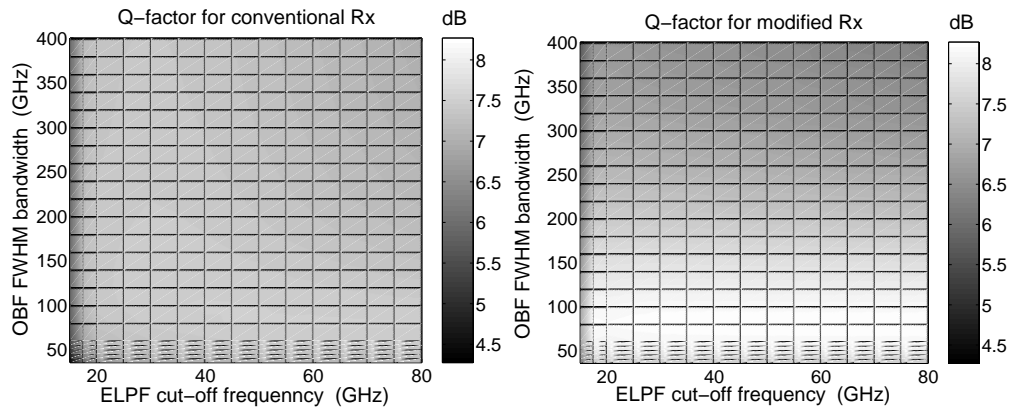


Fig. 5.  $Q$ -factor versus cut-off frequency of the electrical filter and bandwidth of the optical filter for noise-limited transmission. Left, conventional receiver; right, proposed pulse processor-enhanced receiver.

A sensibly different physical picture is obtained when the receiver is applied to noise-limited transmission, as one may see in Fig. 5. In the case of noise-degraded transmitted signals, configuration (B) (with the OBPf just after the EDFA) is used for the proposed receiver in order to reduce the optical ASE-ASE beat noise before signal transmission along the NDF, where the noise is amplified by nonlinear propagation. In Fig. 5, the input pulses to the receiver have the



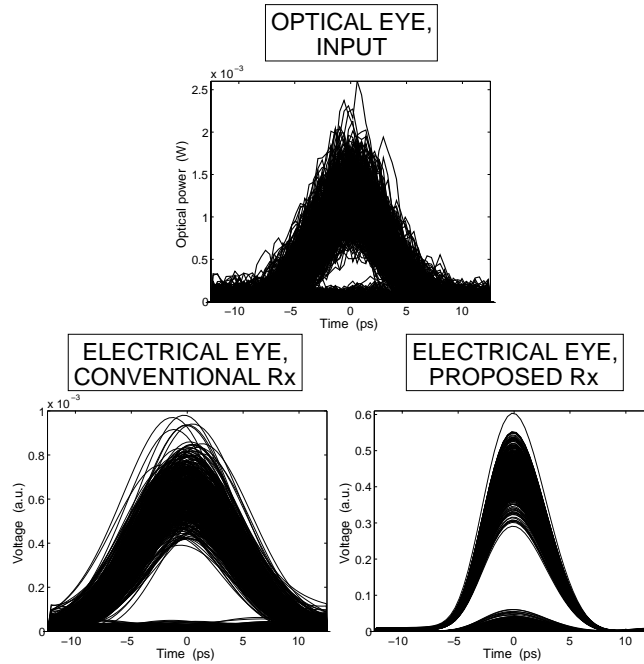


Fig. 6. Eye-diagrams in the receiver for noise-limited transmission.

same duty cycle of approximately 28% as those used in Figs. 3 and 4, and the EDFA gain and the AM parameters are also the same. It can be seen that the receiver performance is mainly determined by the optical bandwidth. For both conventional and modified receivers, narrow OBPB bandwidths performs better and, at a fixed optical bandwidth, the SNR in the detected electrical signals does not vary appreciably with increase of the ELPF cut-off frequency, provided that the cut-off frequency is beyond the ISI limit. We note that the use of large electrical bandwidths without decreasing the SNR is permitted here because the noise contributions from the receiver are neglected in our simulations. Accounting for the receiver noise would make electrical bandwidths of the order of 40 GHz as a typical reasonable choice. Optimum receiver performance is achieved here with an electrical cut-off frequency of 80 GHz and an optical FWHM bandwidth of 60 GHz for both receiver types. The proposed pulse processor-modified receiver performs better than the conventional receiver even when applied to noise-limited transmission, yielding an estimated  $Q$ -factor improvement of 0.7 dB at the optimum receiver bandwidths. An example of signal eye-diagrams in the receiver is shown in Fig. 6. The optimum optical and electrical receiver bandwidths are used. It can be seen that the optical input eye is closed due to a significant amplitude noise on both the pulses and the zero level of the pulses, and to a considerable pulse distortion. The reduction of noise and the pulse reshaping provided by the receiver filters make the eye of the electrical signal rather open. The eye opening detected with the proposed scheme is slightly larger than that in the conventional receiver because of the suppression of timing jitter provided by the AM. We note that the combination of the proposed technique with a saturable absorber, such as a NOLM, which would provide suppression of the amplitude noise in the signal, could improve the receiver performance further especially in the case of noise-limited transmission. We shall address this issue in the future.

Next, we measure the receiver performance as a function of the relative phase detection time. The results are shown in Fig. 7, which illustrates the  $Q$ -factor penalty for the conven-

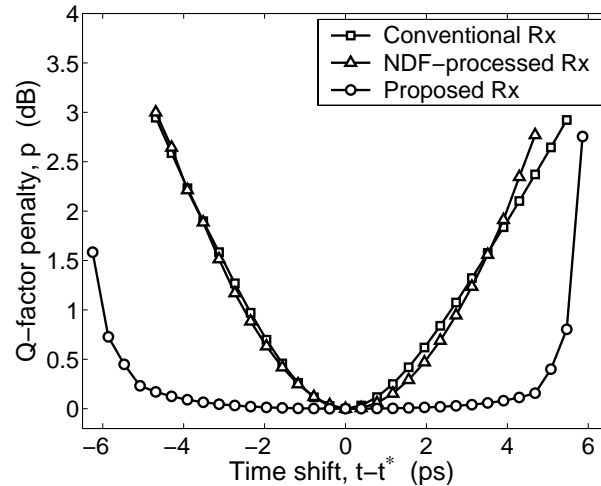


Fig. 7.  $Q$ -factor penalty versus shift from the sampling time for which the  $Q$  is maximal.

tional, the NDF-processed [2, 3], and the proposed receiver as a function of the shift of the time of measurement from the sampling time  $t^*$  for which the  $Q$ -value for each receiver type is maximal. The penalty is defined as  $p = Q_{\max}/Q$ , where  $Q_{\max}$  is the maximum  $Q$ -value measured at  $t^*$ . These measurements are applied to the timing jitter-degraded signals used in Figs. 3 and 4. The parameters of the proposed pulse processor are the same as those used in Figs. 3, 4, 5, and 6, and the optimum optical and electrical receiver bandwidths are employed for each of the receiver types. It is seen in Fig. 7 that when the signals are detected with the conventional method, the decrease of the  $Q$ -factor with increase of the time shift  $|t - t^*|$  follows a parabolic-like characteristic. When the receiver is enhanced by the NDF-based pulse processor, a parabolic-like characteristic is also obtained, which exhibits a slightly larger concavity in the proximity of the vertex. When the proposed method is employed, a rectangular-like characteristic is obtained with a  $Q$ -factor that does not differ appreciably from its maximum value within a wide time window. Estimating the signal phase margin at some reference value  $\bar{p}$  of the  $Q$ -factor penalty as the window of time of measurement where the penalty is less or equal than  $\bar{p}$ , we obtain that the phase margin detected with the NDF-enhanced method is improved by approximately 10% compared to that detected with the conventional method at any  $\bar{p} \leq 1$  dB. The phase margin detected with the proposed method is considerably wider than that detected with both the conventional and NDF-enhanced methods at any  $\bar{p}$  within the considered penalty range. At reference penalties  $\bar{p} \leq 1$  dB, the phase margin improvement over the conventional receiver is of 133% at least. This large increase of the phase margin is mostly contributed by the retiming function of the AM.

The proposed nonlinear pulse processor is particularly effective in suppressing the timing jitter of the pulses. This function, performed in the optical domain, is important for improving the receiver sensitivity. The pulse processor acts in this instance as an optical sampling element that extracts signal amplitudes for data decision. Indeed, once the detected electrical signal arrives at the decision circuit, the reduced fluctuations of the sampling time from bit to bit resulting from the reduction of the optical timing jitter lead to reduced fluctuations of the bit sampled values and, consequently, to an improved SNR. Note that for several reasons such as, for instance, compatibility with high-speed operation and cost efficiency, it is desirable to perform signal processing in the optical domain rather than in the electrical domain. This might



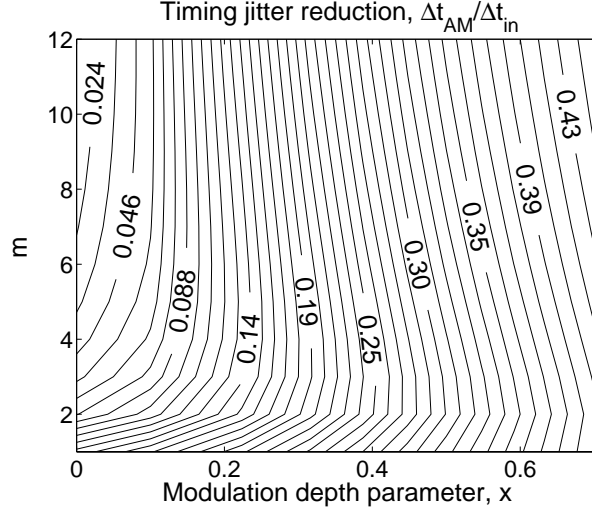


Fig. 8. Timing jitter reduction factor versus modulation depth parameter  $x$  and parameter  $m$ .

become a more and more important issue with the future growth of the channel transmission rates. The retiming capability of the pulse processor is illustrated in Fig. 8, which shows the ratio of the optical signal timing jitter at the AM output to the timing jitter at the pulse processor input,  $\Delta t_{\text{AM}}/\Delta t_{\text{in}}$ , as a function of the modulation depth parameter  $x$  and the control parameter  $m$  in Eq. (1). The calculations are made for the timing jitter-degraded signals used in Figs. 3, 4, and 7. The timing jitter  $\Delta t$  of a pulse train is calculated as the average over all marks in the pattern of standard root-mean-square time position characteristics [8], where the integration for each logical one is performed over the corresponding bit timing slot,

$$\Delta t = \left[ \frac{1}{N} \sum_{i=1}^N (T_i - \langle t \rangle)^2 \right]^{1/2}, \quad (2)$$

$$t_i = \frac{\int_{-T/2}^{T/2} dt t P_i(t)}{\int_{-T/2}^{T/2} dt P_i(t)}, \quad T_i = t_i \frac{\langle P_i \rangle}{\langle P_{\text{tot}} \rangle}, \quad \langle t \rangle = \frac{1}{N} \sum_{i=1}^N T_i.$$

In Eq. (2),  $t_i$  is the time position of the center of mass of the  $i$ -th bit in the pattern,  $P_i(t)$  is the instantaneous optical power of the  $i$ -th bit,  $\langle P_i \rangle$  is the average optical power of the  $i$ -th bit,  $\langle P_{\text{tot}} \rangle$  is the average power of the pattern, and the weighted center of mass  $T_i$  accounts for discrimination of the zero bits against the one bits. To account for more statistical realizations,  $\Delta t$  is averaged over four pseudorandom pulse trains. The modulation peak  $t_0$  in function (1) is set to the average time shift  $\langle t \rangle$  of the pulses incoming to the AM, which is here approximately zero. The evaluated timing jitter at the pulse processor input is  $\Delta t_{\text{in}} = 5.9$  ps. It is seen in Fig. 8 that the proposed pulse processor has an excellent retiming function. For a fixed value of  $m$ , the strength of time restoration increases with decreasing  $x$  (increasing modulation depth), as it was to be expected. For small values of  $x$ , the strength of time restoration increases appreciably with increasing values of  $m$ . Jitter reductions down to 2% are possible. For high values of  $x$ , medium values of  $m$  perform better.

It is also important to investigate the impact of the nonlinearity in the NDF on the receiver performance. Here, we vary the effective nonlinearity in the NDF by tuning the gain of the

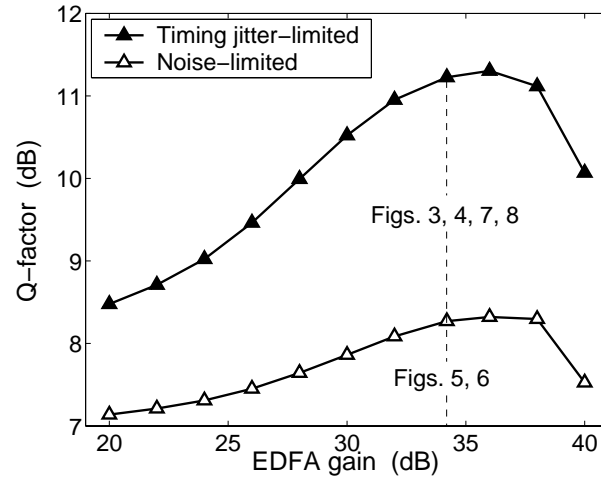


Fig. 9.  $Q$ -factor versus gain of the amplifier.

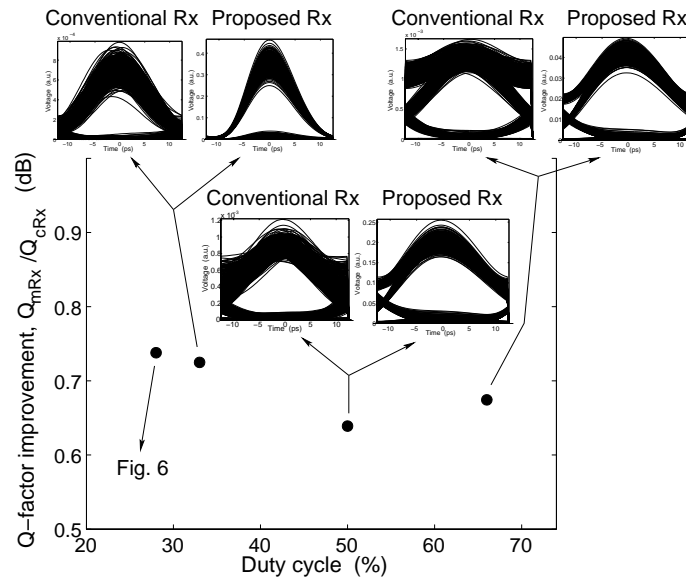


Fig. 10.  $Q$ -factor improvement in the proposed receiver over that in the conventional receiver versus duty cycle of the received pulses. Insets: detected signal eye-diagrams.

optical amplifier. We note that in a wavelength-division multiplexed (WDM) system, one can use a single in-line amplifier for all channels before demultiplexing and per-channel operation of the NDF-AM block. Figure 9 shows the  $Q$ -factor of the detected signal as a function of the amplifier gain for both timing jitter- and noise-limited transmission. The AM parameters are  $x = 0.1$  and  $m = 12$ , and the optimum optical and electrical bandwidths of the receiver are employed. For gains less than the optimum one, less pulse broadening and flattening is achieved in the NDF, while for gains larger than the optimum one, the pulse width after propagation in the NDF is broadened appreciably beyond the timing slot. Both factors diminish the efficiency of the pulse processor and, hence, degrade the receiver performance.

We notice that the applicability of the proposed nonlinear pulse processing technique is not limited to the relatively short duty cycle of the RZ pulses used in the simulation examples so far. Indeed, in the proposed scheme the degree of pulse broadening and flattening in the NDF can be easily controlled by control of the trade-off between the effects of dispersion and nonlinearity in the fiber, for fixed parameters of the pulses to be received. This can be done by varying the amount of pulse amplification by the optical amplifier and/or tuning one or more of the fiber parameters. To validate this idea, we have run exemplary simulations with RZ pulses having the commonly used duty cycles of 33%, 50%, and 66% (corresponding to the FWHM pulse widths of 8.25 ps, 12.5 ps, and 16.5 ps, respectively). The results are shown in Fig. 10, which illustrates the improvement of signal  $Q$ -factor in the pulse processor-modified receiver over that in the conventional receiver,  $Q_{\text{mRx}}/Q_{\text{cRx}}$ , as a function of the duty cycle of the received pulses. In this example, the pulses are received after transmission in the noise-limited transmission system of Figs. 5, 6, and 9, and, therefore, configuration (B) is used for the modified receiver. The gain of the optical amplifier is used as the control parameter over the nonlinear pulse broadening in the NDF, and is adjusted such as to provide a pulse duration approximately equal to the bit duration at the NDF output. The AM parameters are:  $m = 12$  and  $x = 0.1$ . The receiver electrical and optical bandwidths are optimized for each receiver type and each pulse duty cycle. The insets show the signal eye-diagrams in the receiver. It is seen in Fig. 10 that the improvement of signal quality by the proposed method over the conventional method does not depend essentially on the duty cycle of the received pulses. Simultaneous optimization of the system parameters will give improved results.

#### 4. Conclusion

We have proposed a new technique of all-optical nonlinear pulse processing for use at a RZ optical receiver, which is based on an AM or any device with a similar function of temporal gating/slicing enhanced by the effect of Kerr nonlinearity in a NDF. The efficiency of the technique has been demonstrated by application to timing jitter- and noise-limited RZ transmission at 40 Gbit/s. Substantial suppression of the signal timing jitter and overall improvement of the receiver performance has been demonstrated using the proposed method. The performance of the proposed pulse processor-enhanced receiver has been shown to be substantially independent of the duty cycle of the received RZ pulses. The proposed scheme could be used in WDM systems by applying the EDFA and the NDF-AM block before and after signal demultiplexing, respectively. Moreover, the scheme could be combined with a saturable absorber, such as a NOLM, to improve the receiver performance further. This would be especially effective in noise-limited transmission systems.