# The Ways of Reducing the Degradation of Optical Signals and Study the Effect of the Degradation on the Quality of Optical Fiber Communication Systems

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## ABSTRACT

This paper is to analyze the impact of optical signal degradation on the quality of optical fiber communication systems, and enhance the way of reducing the signal degradation mechanism. In this paper, different investigation has been carried out in order to: Investigate the stability of various modulation formats to the effects of chromatic, polarization mode dispersion and nonlinear effects. And achieve the desired interest in the optical communications from the viewpoint of improving the stability to the dispersion, and find the optimum receiver bandwidth at which the system error rate is minimized. And find new ways of compensating chromatic dispersion in communication systems at 40 Gb/s. And find new ways to increase the range of transmission in a communication system transmitters based on semiconductor lasers with direct modulation.

**Keywords:** Chromatic Dispersion, Polarization Mode Dispersion, Semiconductor Lasers, Direct Modulated Lasers, Stability of Different Modulation Formats, Electronic Dispersion Compensation.

# طرق الحد من تدهور الاشارات الضوئية ودراسة تأثير هذا التدهور على كفاءة أنظمة اتصالات الألياف البصرية

**الخلاصة**

تحليل تأثير تدهور الإشارات الضوئية على جودة أنظمة الاتصالات بالألياف البصرية، وتعزيز طرق جديدة للحد من التدهور، عن طريق دراسة وتحقيق الاستقرار لأشكال التضمين المختلفة بالنسبة إلى تأثير التشتت اللوني، وتشتت الاستقطاب والتأثيرات اللاخطية. وتحقيق الفائدة المرجوة من الاتصالات البصرية من ناحية تعزيز الاستقرار بالنسبة للتشتت، وايجاد عرض نطاق ترددي امثل للاستقبال، بحيث تكون نسبة الخطأ فيه أقل ما يمكن. وايجاد طرق جديدة للتعويض عن التشتت اللوني في نظم الاتصالات عند 40 جيجابت/ثانية. وإيجاد طرق لزيادة معدل الإرسال في مرسلات انظمة الاتصالات استنادا الى ليزرات أشباه الموصلات بأستخدام التضمين المباشر.

## INTRODUCTION

Understanding the physical mechanisms which are arising during the signal propagation in the optical waveguides has become particularly relevant in solving one of the most important problems in the field of optical telecommunications (Problems of reducing the dispersion and nonlinear distortion and their effects on optical signals) [1].

In the last decade, the interest in finding new ways of improving optical system against signal degradation is greatly demanded. The reason is because of the ever-increasing transmission rates of information accompanying to the distortion due to chromatic and polarization mode dispersion in proportion to the bit rate. Due to the highly branched networks, the need for their fast reconfiguration dynamic distortion compensation has also become urgent.

Despite the large number of publications devoted to the issue of dispersion and nonlinear distortion of signals, a number of important fundamental issues left on side unexplored or insufficiently explored [2].

In particular, such issues include typical ways to reduce different distortion mechanisms using useful frequency modulation (chirp), present in the laser radiation with direct modulation, methods of electronic dispersion compensation and nonlinear effects and so on.

The practical significance of the work is due to the fact that dispersion compensation and nonlinear distortion mitigation is required for the transfer of data signals in optical fiber communication systems. Improvement and development of new, effective and inexpensive ways to reduce degradation of signals has great practical value, because it allows increasing the speed and distance of data transmission in the existing telecommunications networks.

A predetermined amplitude-modulated signal is formation at a given point of the fiber from phase-modulated or amplitude-phase-modulated radiation provides improved accuracy and range work distributed optical fiber sensors.

**The novelty of the work**

Provides a new method of electronic dispersion compensation - method "time lens", which consists in that the amplitude - modulated signal acquires through a certain distance in the fiber modulator additional phase modulation, resulting in the output of the fiber is formed by an inverted signal.

For the first time it provides a method an amplitude - modulated signal forming at the output of the optical fiber communication line of continuous phase - modulated (AMSF/CPM).

For the first time for communication systems based on lasers with external modulation at a transmission rate of 40 Gb/s formats alternate – mark inversion (AMI), phase – shaped binary transmission (PSBT) and amplitude – shift keying 4-ary (ASK) found the optimum bandwidth of the receiver, in which the effect of chromatic dispersion, polarization mode dispersion and nonlinear effects is minimal.

**Challenges with 400 Gb/s and Beyond**

Future transmission of 400 Gb/s and beyond will employ higher-order modulation formats such as polarization - division multiplexed, quadrate amplitude modulation 16 – (QAM) and other new ways of advanced modulation. In such systems, the chromatic and polarization mode dispersions can be digitally compensated in the electrical domain. However, these systems are susceptible to fiber nonlinear limits. In addition, high data rate communication systems require much higher optical signal to noise ratio to be achieved, about 10 dB improvement in the optical signal to noise ratio will likely be needed for 400 Gb/s systems for fair performance comparable to just 100 Gb/s. The design of the optical system including transmitters, receivers and amplifiers are all play an important role in improving the signal to noise ratio [3]. An additional approach can use new optical fibers that mitigate non-linear impairments to improve the optical signal to noise ratio. Polarization mode dispersion testing, that is defined in [4], is becoming essential in the fiber characterization process, but still one of the most difficult parameter to test, due to its sensitivity to a number of environmental constraints.

**The principle of time lens method**

Error rate selected as a criterion for the quality of the communication system, defined by the formula (1). The encoding signals are only using the format non-return to zero. The optical signal is directly modulated - the laser is transmitted through the fiber, where on it acted chromatic dispersion and nonlinear effects, then got to the receiver, where it happened recognition. The optical signal to noise ratio in all numerical experiments was 20 dB, and the chromatic dispersion coefficient was 18 ps / nm / km. The experiments were carried out for receiver bandwidth at half transmission rate (for 6 GHz). The time limit of the range, which is measured in the center of the electrical signal power at the receiver, coincides with the boundaries of the bit interval of the transmitter. The results of numerical experiments are presented in Fig. (5), where the maximum transmission distance is defined as the maximum distance where the bit error rate (BER) does not exceed the value of the U-12 (the international standard).

It is seen that in the absence of nonlinear effects structured pumping gives a considerable gain in transmission range, but its resistance to nonlinear effects in the conditions described above is worse than that of a conventional pump.

However, standard telecommunications fiber nonlinearity coefficient is typically less than 2W $km^{-1}$, receiving the structured pumping can increase the transmission distance of 30–75% depending on the current logical unit. A new way numerically investigated to deal with chromatic dispersion and nonlinear effects in the fiber when used the laser with direct modulation as a transmitter. This method is the use optical filters to be installed in the communication line after the laser and carries out additional frequency modulation signal.

In the propagation in the optical fiber, pulse is under the influence of dispersion expands. When transmitting a sequence of pulses, this leads to the fact that each pulse tends to occupy the bit interval allowed for its neighbor. The most vulnerable for chromatic dispersion is a sequence of 101, blurred units in the bit interval, retracted to zero add up and at the receiver it is recognized as a unit.

In a laser with a controlled chirp, creates destructive interference between the units, they are added in the opposite that, ultimately, significantly increases the stability of the system to the dispersion. If the form of individual pulses were rectangular, it would be achieved in the case where a logic-zero frequency 6GHz frequency less than the logical unit. Then, during the time interval corresponding bits (100 ps for a transmission rate of 10 Gb/s).

In the transmitter, based on direct modulation laser destructive interference is achieved by a certain choice of parameters of the laser. Shift between two logical units in this case with a minimum BER is different. The signal at the output of the transmitter, providing destructive interference, similar to the format signal AMI and even without the optical filter has a high resistance to chromatic dispersion.

At the transmitter, with such a controlled chirp signal then enters the optical filter. Here, via the adiabatic chirp "0" frequency "separated" from "1", and the power corresponding to logical zero, is strongly attenuated (in our model 10 times). This leads to a significant increase in the error rate at the output of a laser with a controlled chirp. An increase in the error rate at the output of the laser is usually accompanied by an increase chirp. In a laser with controlled dynamic chirp is not increased, on the contrary, properly select the parameters of the laser and its pump can significantly weaken it to the filter, even to the detriment of the error rate - the coefficient of extinction still increases after filtration. The above described effects in a laser with controlled chirp transmitter allow several times to increase the transmission range by increasing the stability of dispersion. In the future, the signal at the output of a laser with a controlled chirp will be called non-return to zero - current mode logic (NRZ – CML), considering the effect of the filter as the formation of the corresponding modulation format. Signal without filtering, but destructive interference between the logical units will be similar to the format of alternating polarity called AMI.

**Results**

After studying the combined effects of chromatic dispersion and nonlinear effects for various modulation formats such as non-return to zero NRZ, return to zero (RZ), Carrier-Suppressed Return-to-Zero (CS-RZ), PSBT, 4-ary ASK, AMI at transmission rate of 40 Gb/s. It has been considered that the optical source is an ideal externally modulated source. The quality parameters characterize the stability of the system to the effects of polarization mode dispersion is the bit error rate BER, which is calculated from the approximate formula recommended by the international standard ITU-T O.201:

$$BER(Q) = e^{-\left(\frac{Q}{\sqrt{2}}\right)^2} * \frac{a_0 + a_1\frac{Q}{\sqrt{2}} + a_2\left(\frac{Q}{\sqrt{2}}\right)^2}{\left[b_0 + b_1\frac{Q}{\sqrt{2}} + b_2\left(\frac{Q}{\sqrt{2}}\right)^2 + b_3\left(\frac{Q}{\sqrt{2}}\right)^3\right]\sqrt{\pi}} \quad \ldots (1)$$

Where

$a_0 = 1.58061484$, $a_1 = 1.34116145$, $a_2 = 0.4000212$, $b_0 = 1.8065343$, $b_1 = 3.6837483$, $b_2 = 2.80734337$, $b_3 = 1$, $Q-$ quality factor of the optical signal:

$$Q = \sqrt{\frac{OSNR}{\frac{1+ER^2}{1-ER^2} * \frac{B_e}{B_0}}} \quad \ldots (2)$$

Where

$B_e-$ is the electrical receiver bandwidth, $B_0-$ optical signal bandwidth, $ER = P_1/P_0-$ is the factor blanking, $P_1$ and $P_0-$signal power corresponding logical unit and logic zero respectively (or any other neighboring logical values in case of a multiple format) in the middle of the bit interval. In the experiments work it has been implemented that is the relation bandwidth of the optical filter at the input of receiver to the data transfer rate (40 Gb/s).

Figure (1) shows that the communication system with various modulations formats are subject to varying degrees of degradation arising from increasing inter-symbol interference and noise at the receiver with respect to the increase in the bandwidth.

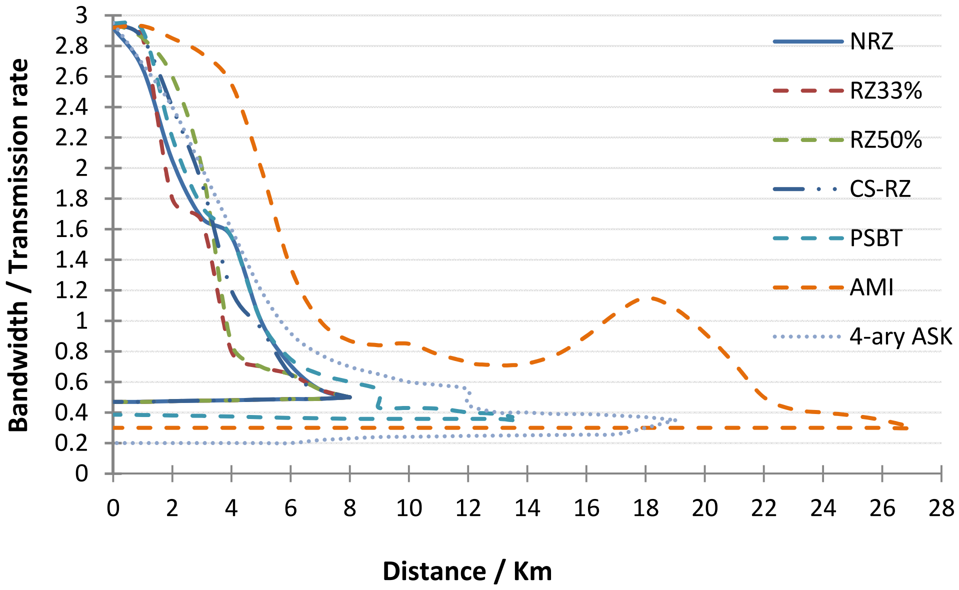


**Figure (1): The relationship of the receiver bandwidth with the fiber length for different modulation formats.**

For each format has been found optimal bandwidths of the receiver at which achieves the maximum transmission distance with a chromatic dispersion coefficient 18 ps / nm / km and BER $<10^{-9}$.

It is shown, formats PSBT, AMI and 4-ary ASK allow narrow bandwidth of the receiver at the maximum for format non-return to zero transmission distance, respectively 24%, 40% and 60% compared to non-return to zero.

At 40 Gb/s, the maximum transmission distance was achieved by using the format alternating polarity (with BER $<10^{-9}$). As compared with non-return to zero encoding formats, it was increased by 3.5 times. The 4-ary ASK and PSBT also showed a great stability to chromatic dispersion compared to the non-return to zero via their transmission range where it was increased to 2.5 and 1.8 times respectively. Further, it has been shown that the rate of transmission in systems at bit rate of 40 Gb/s using a majority binary formats at constant chromatic dispersion of 18 ps/nm/km decreases almost linearly with an increase in the coefficient of nonlinearity, Figure (2). Among them, It has been shown that the most stability format of coding to the nonlinear effects was return to zero with a duty cycle of 33%; the increase in the nonlinearity coefficient from 0 to 35 $W^{-1}km^{-1}$ maximum transmission distance was reduced by only 0.1% [5,6,7].

After studying the stability of different modulation formats the influence of polarization mode dispersion. The criterion for the quality of the communications line served the bit error rate [8,9].

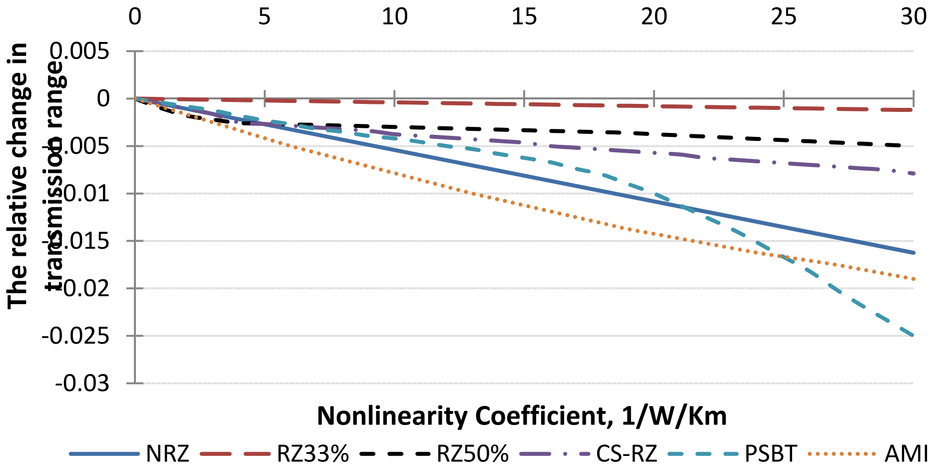


**Figure (2): The relationship of the relative change in transmission range with the nonlinearity coefficient for different modulation formats.**

Numerical experiments have shown that for communication systems with an acceptable level of quality factor and (BER $<10^{-9}$), it is necessary that the bandwidth of the receiver lying in the range of 0.5 - 1.2 transmission rate as shown in Figure (3).

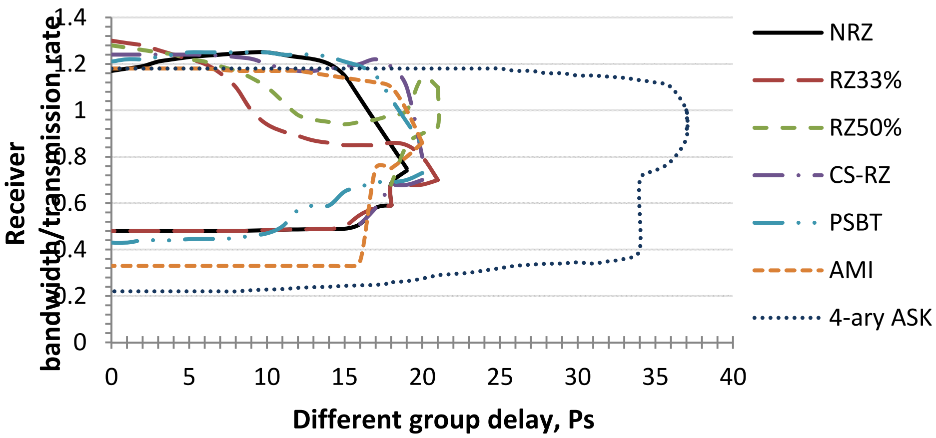


**Figure (3): The relationship of the receiver bandwidth with the fiber length for different modulation formats.**

It was shown that the amplitude-phase modulation format with alternating polarity, as well as 4-ary modulation format, can extend this range by moving its lower limit of the transmission rate, respectively, to 0.35 and 0.2, that other things being equal, it can be used for these formats receivers with less bandwidth. For all the above formats found optimal values of the bandwidth of the receiver, at which the maximum transmission distance. Further, it has been explored that the 4-ary ASK is significantly more stable to polarization mode dispersion. Moreover, the transmission range can be also increased by almost 2 times compared with the non - return to zero coding format. The maximum allowable difference group delay (with BER $<10^{-9}$) among other coding formats mentioned earlier was achieved with return to zero format with a duty cycle of 50%. However, the distance was no more than 50%.

After studying the optical fiber communication systems based on semiconductor direct modulated lasers [10,11,12,13,14]. Another numerical study was done depending on the quality of communication lines from parameters and pump current direct modulated lasers. All parameters were varied in small range close to the values inherent in the actual transmitter used in optical fiber communication systems. As a criterion for the quality of the line used by the error rate BER that is calculated by using equation (1) for a fiber length of 30 km and the optical signal to noise ratio of 20 dB. It has been proposed several ways to improve the quality of such systems. It has been shown that it is possible to reduce the dynamic (transition) chirp by reducing the current strength between the two logical values of the pumped signal that has been achieved by reducing the limit parameter cavity resonator, reducing the broadening factor and increasing the nonlinear saturation parameter.

If the modulation depth decrease in transition leads to increase in transmission distance. It is also shown that there is an optimum difference current strength between the two logical values of the pumped signal and the optimum value of the limiting factor of the cavity resonator, in which the system is based on direct modulation laser, ceteris paribus has the highest quality. Furthermore, the transmitter that based on direct modulation lasers using a structured pump provides a significant improvement of the quality of communication systems at 10 Gb/s in the optimization of the receiver parameters and structure of the pump signal. As a result, the conditions under which the transmission distance using such transmitters is increased by 75% compared to systems using standard transmitters by direct modulation lasers. The parameters of the direct modulation lasers, in which the transmitter implemented on the basis of the encoding format, were found with providing destructive interference between logical units, separated by a logical zero.

It is shown that this format is 2 times more stable, and by using a special optical filter is 5 times more stable to chromatic dispersion than non - return to zero format. The circuit implementation of such a system with an optical filter is shown in Figure (4). Figure (5) illustrates the relationship of power before and after filtering process, the frequency and phase of the signal at the output the chirp-managed laser on time.

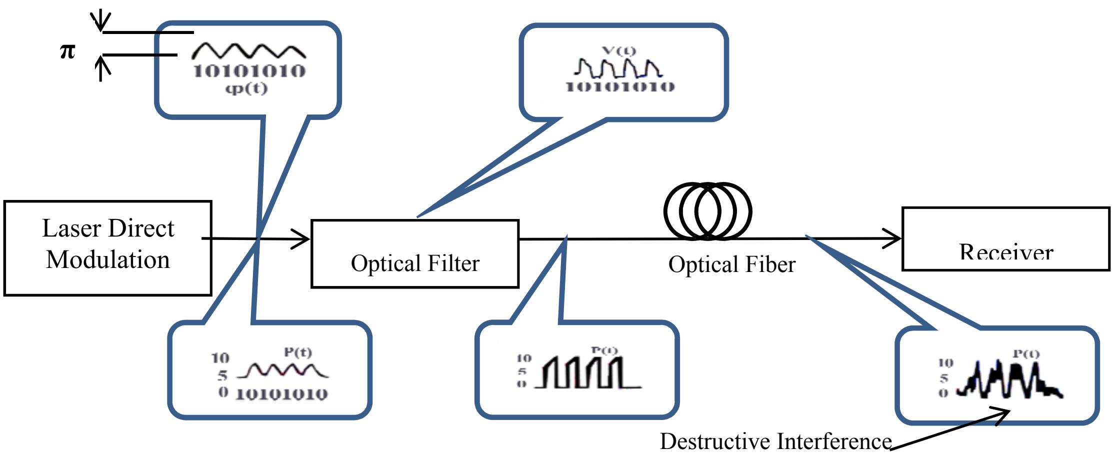


**Figure (4): Diagram the implementation of the coding format, providing destructive interference between logical units and separated by a logical zero**

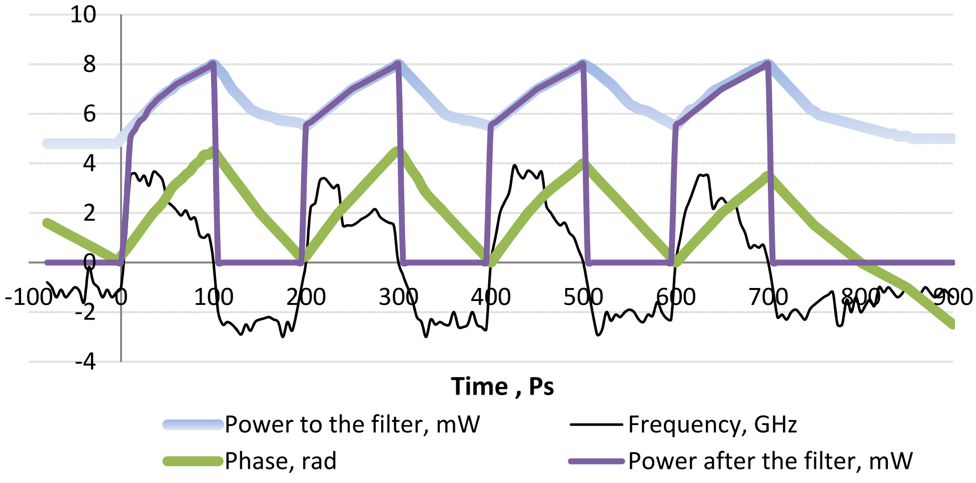


**Figure (5): The time dependence of power after and before the filter, the phase and frequency of the signal at the output of a system.**

More, we present and numerically investigate a new method of electronic dispersion compensation, the method of "time lens" [15,16,17,18], the implementation of the scheme is shown in Figure (6). The optical signal after amplitude modulation hit the first section of optical fiber length $L_1$, in which it acted dispersive and nonlinear effects. Further, after conversion into the phase modulator, phase signal acquired raid additional $\Delta\varphi$ :

$$\Delta\varphi = \alpha(t - t_{mid})^2 \qquad \dots (3)$$

Where $t_{mid}$ −time in the middle of the transmitted bit sequence, $\alpha$ −modulation parameter. Then the signal passes another segment of the fiber length $L_2$ and got on receiver.

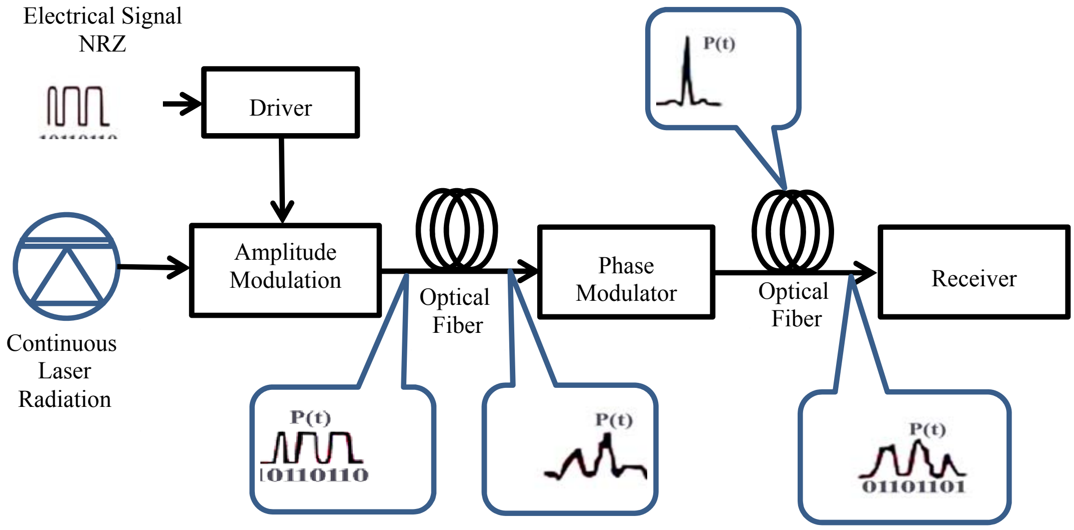


**Figure (6): Scheme the implementation of the method of "time lens"**

The method of "time lens" is based on the symmetry of the wave equation for the spatial and temporal coordinates. The signal is distorted under the influence of chromatic dispersion; as a result of phase modulation is first compressed, and its power focused at the center of the time interval corresponding to the entire bit sequence. After that the signal is expanded, and a distance $L_2$ at predetermined parameter α to the form of the input signal, but it is reflected symmetrically about the center (i.e., inverted).

It was shown that the maximum power of the signal increases significantly at a certain distance in the second fiber section (for the focal length "time lens"). As a result of numerical simulation we plotted the bit error rate in optical fiber communication line on the distance for different values of the parameter α, see Figure (7). It has been established that the selection of α can control the range of the transmission rate information.

The dependence of the quality of the communication line based on "time lens" on the phase modulation parameter α for various values of the bandwidth of the receiver. It is shown that the minimum the bit error rate for all α lies in the vicinity of the receiver bandwidth, equal 0.8 the transmission rate.

The possibility of implementing a dynamic phase modulation (for this purpose in (Figure.6) is enough to add the driver module that will control on the phase modulator), which will use the method of "time lens" in modern reconfigurable optical communication networks.

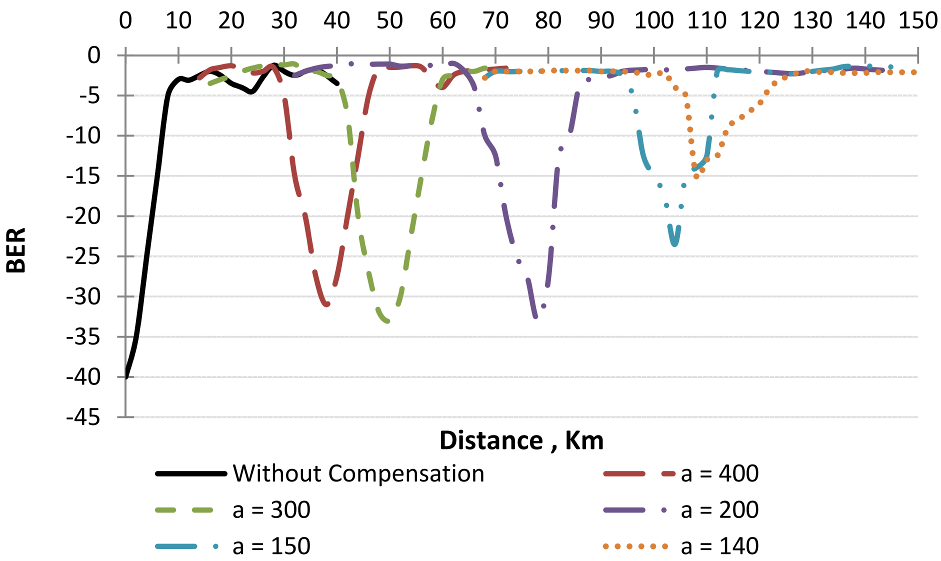


**Figure (7): The relationship of the bit error rate with the distance for parameters various values of the phase modulation**

It is shown that the "time lens" close to linear compensation on stability to nonlinear effects, while the nonlinearity coefficient greater than 27 W-1km-1, the quality of communication lines of optical fiber based on the "time lens" higher than the linear dispersion compensation (at BER>10-12. Thus, instead of dispersion compensating fiber used cheaper standard telecommunications fiber and can still be dynamic dispersion compensation and nonlinear effects. It is found that using the method of "time lens" can transmit information at a rate of 40 Gb/s over a distance of approximately 110 km without additional dispersion compensating modules. The numerically proposal investigated a fundamentally new way of forming an amplitude-modulated signal at the output of the optical fiber communication line of continuous phase-modulated. The scheme is shown in Figure (8).

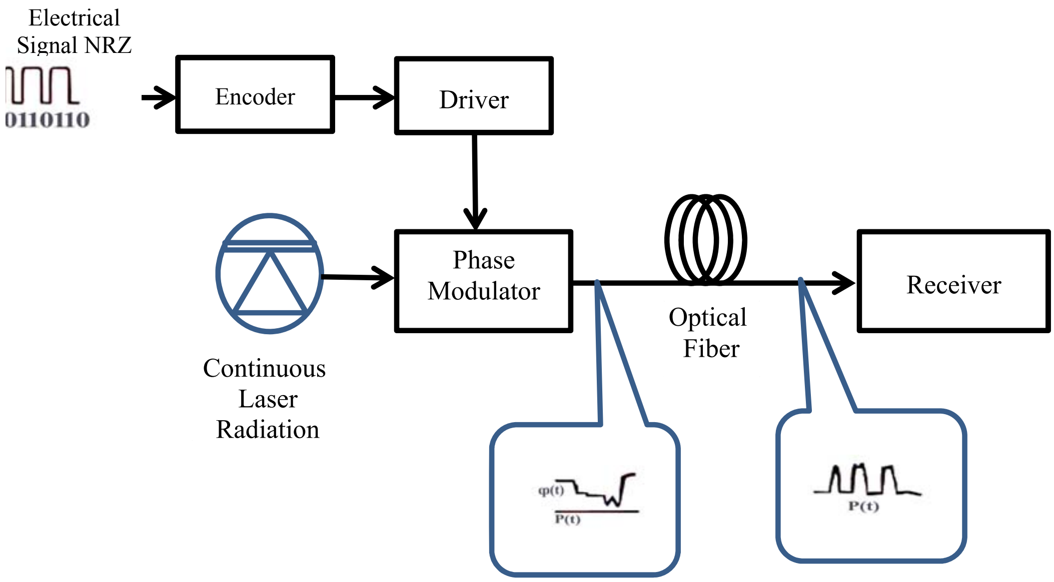


**Figure (8): Scheme electronic dispersion compensation method**

It is the solving of the problem of finding the kind of phase modulation $\varphi(t)$ of continuous laser by iterative method, which ensures the formation of the desired amplitude modulated signal at the output of the optical fiber lines, Figure (9).

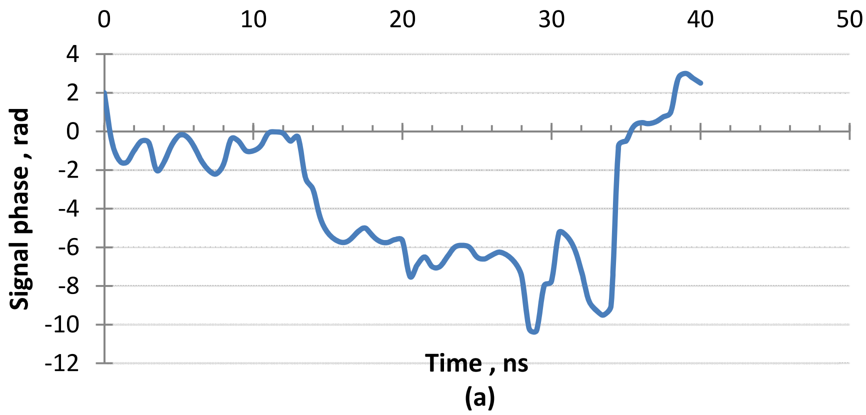


**Figure (9): a) the distribution of phase of continuous laser at the output fiber.**

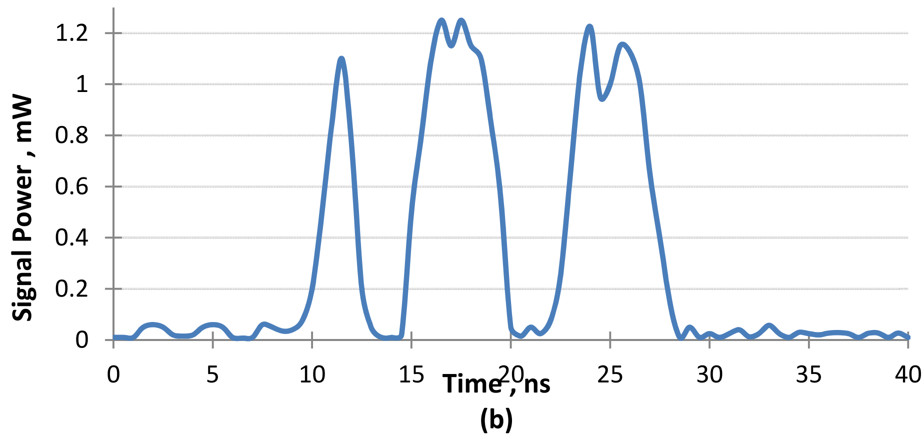


**Figure (9): b) The relationship of the signal power with the time at the output fiber. The binary sequence 10110110. Transmission rate 40 Gb/s modulation format non - return to zero, fiber length of 1000 km.**

It was shown that the transmission of information at a rate 40 Gb/s using the (AMSF/CPM) on a distance of over 1700 km with the error ratio, does not exceed $10^{-12}$. A comparison was made between electronic dispersion compensation by (AMSF/CPM) and linear dispersion compensation at different values of the input power light and the length of optical fiber communication line. Distances were found in the vicinity of which, other things being equal, dispersion compensation and nonlinear effects by (AMSF/CPM) is more effective (for example, 500 km, 1,200 km and 1,600 km at transmission rate of 40 Gb/s). The final results estimates that the accuracy of the results provided by study of techniques and thoroughness of numerical measurements, which performed on modern and high-quality equipment, as well as many of numerical experiments applied and shows the absence of conflict between the results obtained and the results of other research groups given in the references.

**DISCUSSION**

1. From the amplitude modulated signal, supply at the input of the optical fiber can by using a phase modulator located at a certain distance in the fiber, at the fiber output shape inverted signal. This phenomenon can be used for effective electronic dispersion compensation in optical fiber communication system.
2. From continuous phase-modulated radiation at the input fibers can generate at its output a predetermined amplitude modulated signal. This phase modulation can be used to obtain the efficient transmission of information over long distances.
3. For a specific choice of the coefficient of non-linear saturation, limiting factor of the cavity resonator and the shape of the laser pump with direct modulation in the transmitter based on it can provide destructive interference between two logical units separated logical zero. System using that transmitter at other equal conditions, it allows increase the range of transmission of information in two times, and by using special optical filters increase in 5 times, compared to the standard binary format.

## CONCLUSION

In conclusion, different points have been figured out during this paper we can state then as follow:

1. It is shown that the transmitters on the basis of direct modulated lasers using a pump structured provide significant improvement of the quality of communication systems at 10 Gb/s in the optimization of receiver and structure of the pump signal. The conditions are found in which the transmission range using such transmitters is increased by 75% compared to systems using standard transmitters on the basis of lasers with direct modulation.
2. Found laser parameters with direct modulation, in which the transmitter it is based on the implemented encoding format, providing destructive interference between logical units separated by a logical zero. It is shown that this format is 2 times more stable and using a special optical filter is 5 times more stable to chromatic dispersion than the standard binary format.
3. Study the stability of various binary modulation formats, as well as a pseudo three-level format PSBT to polarization mode dispersion at a transmission rate of 40 Gb/s have shown that to obtain communication system with an acceptable level of quality (BER $<10^{-9}$), it is necessary that the bandwidth of the receiver lying in the range 0.5 - 1.2 rate. It is shown that the amplitude-phase format with alternating polarity, as well as 4-level format of 4-ary ASK can extend this range by moving its lower bound, respectively, to 0.35 and up to 0.2 rate that, other things being equal, can be used for these formats receivers with lower bandwidth transmission. For all the above optimum values formats found receiver bandwidth in which achieved maximum different group delay.
4. It is shown that the multi-level formats more stable to polarization mode dispersion than binary. Ceteris paribus format 4-ary ASK increases the allowable different group delay almost 2 times in comparison with the non – return to zero practically at any receiver bandwidth. The maximum allowable different group delay (with BER $<10^{-9}$) among other binary formats was achieved using return to zero format with a duty cycle of 50%, but an increase in the allowable different group delay compared to them was not more than 0.5%.
5. In term of chromatic dispersion it is shown Formats that PSBT, AMI and 4-ary ASK allow narrow bandwidth receiver, ceteris paribus, respectively 24%, 40% and 60% compared to the non – return to zero. For each format found optimal bandwidths of the receiver, at which the maximum transmission distance with a coefficient of chromatic dispersion 18 ps/nm/km.
6. The transmission distance compared with non – return to zero -coding, it is increased by 3.5 times. The 4-ary ASK and PSBT also showed great stability to chromatic dispersion than non – return to zero: using them transmissions distance increases respectively 2.5 and 1.8 times.
7. Investigation of the stability of various formats to nonlinear effects showed that the range of transmission systems at 40 Gb/s using a majority binary formats at constant chromatic dispersion of 18 ps/nm/km decreases almost linearly with an increase in the coefficient of nonlinearity.
8. A new method of electronic dispersion compensation, which consists in the fact that the amplitude-modulated signal gets through a certain distance in the fiber modulator further phase modulation, resulting in the output of the fiber is formed an inverted signal. Electronic dispersion compensation method is called "time lens"

because of the analogy with the conventional lens, arising due to the symmetry of the wave equation for the spatial and temporal coordinates. The possibility to use it to transmit information at a rate of 40 Gb/s over a distance greater than 110 km without dispersion compensating fiber, including a reconfigurable networks.

9. Describes one possible implementation schemes (AMFS/CPM). Method (AMFS/CPM) proposed to use to transmit information. The possibility of transmitting information at a distance of over 1,600 km at speed of 40 Gb/s and BER, not more than $10^{-12}$.

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