Title: Method and device for handling optical pulse signals

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A B S T R A C T

A technique for handling an optical pulse signal, wherein the handling includes one or more operations out of: pulse shaping, treatment of nonlinearity and monitoring; the technique uses a device capable of performing a cascaded second harmonic generation (SHG) with respect to a particular fundamental harmonic (FH), and comprises:

selecting in the device a particular optical path length suitable for performing at least one of the above operations with respect to an incoming optical pulse signal carried by a wavelength defined by the particular fundamental harmonic (FH),

conveying the incoming optical pulse signal carried by the defined wavelength along the selected optical path in the device,

obtaining from the device an output optical pulse signal at the fundamental harmonic (FH), wherein the treatment of nonlinearity and/or the pulse shaping are performed, and/or obtaining an output optical pulse signal at the second harmonic (SH) for further monitoring it and judging about the input optical pulse signal.
FIG. 2A

FIG. 2B
Complete Specification

Applicant(s):
LIGHTSCAPE NETWORKS LTD.

Invention Title:
METHOD AND DEVICE FOR HANDLING OPTICAL PULSE SIGNALS

The following statement is a full description of this invention, including the best method of performing it known to me/us:
Method and device for handling optical pulse signals

Field of the invention

The present invention relates to a technology for pulse shaping, treatment of non-linearity and monitoring in optical communication networks, preferably in optical fiber links. The present application is a Continuation-In-Part to a US patent application, Serial number 09/780,572, filed February 12, 2001.

Background of the invention

Three basic physical factors, that are known as limiting the achievable bit-rate in optical communication links, are chromatic dispersion, power losses and non-linearity. It is well known that power losses can be compensated by all-optical Erbium-doped or Raman amplifiers periodically installed into a long fiber link. Dispersion can also be compensated by means of periodically inserted relatively short elements with the opposite sign and large absolute value of the dispersion, which makes it possible to have the average dispersion nearly equal to zero. As such dispersion-compensating elements, a specially fabricated fiber, or very short pieces of a fiber with the Bragg grating written on it, may be used.

Nonlinearity, which manifests itself as a nonlinear phase shift accumulated by a light signal while being transmitted via an optical fiber, is generated by the so-called Kerr effect in glass. Owing to this effect, the refraction coefficient of the optical material changes with the intensity of the optical signal according to the following formula:

\[ n = n_0 + K|E|^2, \]  

where \( K \) is the Kerr coefficient.
WO 00/49458-A1 describes a method and an apparatus for compensating optical non-linearity in optical devices and transmission systems. Two second order interactions are cascaded in phase-mismatched second harmonic generation to accumulate a non-linear phase shift of a fundamental wave. The non-linear phase shift can be set to provide a desired amount of non-linearity compensation. Compensation takes place in a compensating medium having a negative effective non-linear refractive index at the design operating conditions of the compensating medium. Compensators incorporating these principles may be incorporated as passive or active components in optical transmitters, repeaters or receivers. Active components may be tuned by varying the operating condition of the compensating medium, for example by controlling temperature or applied stress. Embodiments of the invention use the compensator as pre- or post-compensators in an optical amplifier, to eliminate or reduce self-phase modulation in the optical amplifier that occurs as a result of the Kerr effect.

C. Pare et al. in their paper “Split compensation of dispersion and self-phase modulation in optical communication systems” (Optics Letters, 1 April 1996, Vol 21, No.7, p.459-461, Opt. Soc. of America) discuss an idea of alternating the sign of the non-linearity along with the sign of the local dispersion by using a (generally, unspecified) medium exhibiting simultaneously a negative Kerr coefficient and specially tailored dispersion. The authors briefly mention that available non-linear media with a negative Kerr coefficient may be semiconductor wave-guides or media utilizing the cascading mechanism. The authors further point out that, though these materials are only available in the form of short samples with the size ~ 1 cm, the non-linearity of the media might be strong enough to compensate for kilometers of low fiber non-linearity, using pre-amplification if necessary.

It is necessary to note that their estimate was too optimistic: in fact, the semiconductor wave-guides are not acceptable at all, due to the strong two-photon absorption in them; as for the SHG materials, a realistic estimate shows
that, in order to compensate the non-linear phase shift accumulated in a typical span of the fiber ~ 50 km long, the necessary optical path in the second-harmonic-generating material must be no less than ~ 5 m.

According to one possible way of the full signal restoration discussed in the paper, the dispersion compensation and negative Kerr effects must occur simultaneously, using, for example, a grating structure created on a non-linear wave-guide with a negative Kerr coefficient. Another possible way proposed in the article was to split the compensation process, i.e., the dispersion compensation can be applied first and then, in the next step, the Kerr-induced non-linear effects would be cancelled.

The SHG media known in the art can be represented, inter alia, by nonlinear optical crystals capable of producing higher harmonics of an optical signal from its fundamental harmonic. Such crystals, for example potassium titanyl phosphate (KTP), potassium dihydrogen phosphate (KDP), barium borate optical crystals (BBO) and the like have found their use in various types of laser generators. Examples of such systems can be found in JP 08201862 A2, US 6047011, and others.

Notwithstanding the possible degree of the compensation of the dispersion and nonlinearity, they cannot be completely neglected, as they alter the shape of pulses on which the standard non-return-to-zero (NRZ) format of the data transmission in fiber-optic links is based. Ideally, a pulse representing a “one” bit of data must have a rectangular shape. In reality, the nonlinearity and dispersion convert it into a smoothed signal which is usually close to a Gaussian. The deviation of the data-carrying pulses from the ideal rectangles gives rise to problems produced by overlapping of their extended “tails” belonging to adjacent pulses. The tail overlapping of such tails may give rise to the appearance of parasitic maxima between the “one”-bits, which poses an additional factor limiting the achievable bit-rate, known as inter-symbol interference (ISI). While a partial solution to this problem may be provided by the above-mentioned dispersion compensation, only strong reshaping of the
Gaussian pulses (i.e., periodic restoration of the desired near-rectangular form) would provide for a complete solution of the ISI problem.

T. Zhang and M. Yonemura, in the paper “Pulse Shaping of Ultrashort Laser Pulses with Nonlinear Optical Crystals” in Jpn. J. Appl. Phys., Vol. 38 (1999), pp. 6351-6358, describe a technique which uses a time-delay optical crystal and a Type-II KDP optical crystal for pulse shaping of a set of two ultrashort pulses carried by the fundamental harmonic. In order to achieve pulse shaping, the interacting pulses must first satisfy the condition that the group velocity of the second-harmonic wave is close to the average group velocity of the two fundamental-harmonic pulses. If this condition is met, pulse shaping is possible by correctly selecting the fundamental intensity, intensity balance, delay time and crystal thickness.

Neither of the above-mentioned references propose a practical method/device for pulse shaping and compensation of non-linearity in fiber-optic links having various lengths, values of the fiber etc.

Further, there is a known technique for monitoring of optical pulse transmission by splitting the pulse signal and obtaining information on the transmission parameters from a minor split out portion of the signal.

Object of the invention

It is the objective of the invention to provide a method, a device and a system for pulse shaping, control of non-linearity and/or monitoring in telecommunication fiber links.

Summary of the invention

According to a first aspect of the invention, the above object can be achieved by providing a method for handling an optical pulse signal, the handling including at least one of operations for: pulse shaping, treatment of nonlinearity and monitoring, the method comprising steps:
providing a signal handling device capable of performing a cascaded second harmonic generation (SHG) with respect to a particular fundamental harmonic (FH),

selecting an optical path length in said signal handling device, suitable for performing at least one of said operations with respect to an incoming optical pulse signal carried by a wavelength defined by said particular fundamental harmonic (FH),

conveying the incoming optical pulse signal carried by said wavelength along the selected optical path in said signal handling device,

obtaining from said signal handling device at least one output optical pulse signal from a list comprising:

- an output optical pulse signal at the fundamental harmonic (FH), wherein the treatment of nonlinearity and/or the pulse shaping are performed,

- an output optical pulse signal at the second harmonic (SH) for further monitoring it and judging about said input optical pulse signal.

In one preferred version of the method enabling performing the operation of nonlinearity treatment, the method comprises selecting such an optical path length for conveying the incoming optical pulse signal with a known amplitude via the signal handling device, that is substantially close to the length upon passing which the output optical pulse signal at the fundamental harmonic (FH) reaches the maximum peak power.

In another preferred version of the method, ensuring performing the operation of pulse shaping, the method comprises selecting such an optical path length for conveying the incoming optical pulse signal with a known amplitude via the signal handling device, that is substantially close to the shortest optical path length upon passing which the output optical pulse signal at the fundamental harmonic (FH) reaches the maximum peak power.

In yet a further version of the method, allowing for the monitoring operation, the method comprises selecting such an optical path length for
conveying the incoming optical pulse signal via the signal handling device, enabling obtaining from said device the output optical pulse signal at the second harmonic (SH) with a non-zero peak power for monitoring the incoming optical pulse signal carried by the fundamental harmonic (FH).

Principles of selecting the optical path length will be explained in the detailed description of the invention.

To obtain a required optical path length, the method preferably comprises passing the signal along a multi-segment trajectory in said device, thereby arranging an extended optical path.

One possibility to attain the selected optical path length is to convey the incoming optical pulse signal via a multi-segment “zig-zag” trajectory by arranging one or more internal reflections in the signal handling device.

In the method, the signal handling device is based upon an element selected from the following non-exhaustive list including: a second harmonic generating (SHG) optical crystal and a second harmonic generating (SHG) polymer fiber, both known as elements producing nonlinearity or non-linear phase shift.

According to the most preferred version of the method, it further comprises a step of ensuring that the sign of the Kerr effect created by said element to said wavelength defined by the fundamental harmonic is negative. In this case, the method enables the nonlinearity treatment in the form of compensation of the positive nonlinearity usually accumulated in said incoming optical pulse signal due to conventional positive Kerr effect of optical fibers.

It should be emphasized that, unlike the nonlinearity compensation, the pulse shaping and the monitoring can be achieved by using the device producing nonlinearity of any sign. Likewise, a positive nonlinearity adjustment being a specific case of the nonlinearity treatment is provided, when necessary, using the device inducing the positive Kerr effect.

The method is most efficient for gradual compensation of the nonlinearity and/or gradual pulse shaping in the fiber optic link with optional
simultaneous signal monitoring, and comprises an additional step of conveying the outgoing optical signal via a chain including at least one additional signal handling device, and wherein the devices in the chain are spanned by sections of the optical fiber link. In other words, if more than one said devices are inserted in the link and spaced from one another, each of them will contribute to the optical signal handling from the point of nonlinearity treatment, pulse shaping and/or signal monitoring.

By selecting the kind of the device(s), the total length of the optical path in said one or more device(s), and lengths of said one or more sections of the optical fiber link, the obtained results of the signal handling can be adjusted.

The proposed method is also applicable to a case of multi-channel transmission of optical data, where each of the optical channels transmits a specific optical signal at a particular optical wavelength. Usually, the SHG devices are capable of generating second harmonics to a limited spectral range of respective fundamental harmonics defined by wavelengths close to one another. Therefore, the method may be applied to the WDM (Wavelength Division Multiplexing) transmission format, where wavelengths of the optical channels slightly differ from each other.

The proposed method can be utilized in a multi-channel transmission system by performing operations of the basic method with respect to each particular optical channel.

According to one version, the optical pulse signals of different said optical channels are applied to and conveyed via respective different said signal handling devices.

In an alternative version of the method, it comprises conveying the optical pulse signals of different channels via one and the same common signal handling device.

In a further, more promising version, the optical pulse signals of different said optical channels are applied and conveyed via respective different layers of one and the same common pulse treatment device.
The last two versions are suitable for such transmission formats where the wavelengths of different optical channels are close to one another, and provided that the common signal handling device performs its SHG cascaded function in response to the wavelength of each of said multiple optical channels.

If results of the pulse treatment are nonuniform for different optical channels in the multi-channel transmission (which is usually the case), optical channels with better results (say, better compensation of nonlinearity/ more effective pulse shaping) can be used for transmitting information having higher priority.

In accordance with a second aspect of the invention, there is provided a device for handling an optical pulse signal from the point of at least one of the following operations: pulse shaping, treatment of nonlinearity and signal monitoring,

the device being capable of performing a cascaded second harmonic generation (SHG) with respect to a particular fundamental harmonic (FH),

the device being characterized by such an optical path length selected for an incoming optical pulse signal carried by a wavelength defined by said particular fundamental harmonic (FH), that upon conveying said incoming optical pulse signal along the selected optical path, the device enables obtaining at least one output optical pulse signal from a list comprising:

- an output optical pulse signal at the fundamental harmonic (FH), wherein the treatment of nonlinearity and/or the pulse shaping are performed,

- an output optical pulse signal at the second harmonic (SH) suitable for further monitoring and judging about said input optical pulse signal.
The signal handling device comprises a second-harmonic-generating (SHG) element, preferably constituting an SHG optical crystal selected from a non-exhaustive list comprising KTP, KDP and BBO.

It should be noted that the Inventors are first to propose design of a device for handling an optical pulse signal, if applied at a particular wavelength, from the point of at least one of the following operations: pulse shaping, treatment of nonlinearity and signal monitoring, wherein the device comprising

- an SHG element for performing a cascaded Second Harmonic Generation with respect to a Fundamental Harmonic (FH) defined by said particular wavelength,
- said element being covered by mirror surfaces at least at its two opposite facets and leaving at least two windows at said opposite facets for an incoming optical beam and an outgoing optical beam respectively, the arrangement being such to arrange one or more internal reflections of the optical beam if passing between said two windows, thereby providing an extended optical path.

The extended optical path preferably has a length enabling obtaining an outgoing optical pulse signal on the fundamental harmonic (FH) with a peak power close to maximum and/or an outgoing optical pulse signal on the second harmonic (SH) with a non-zero peak power.

According to one specific implementation, the element (preferably the SHG crystal) has a cubic form and is covered at its two opposite facets by mirror surfaces (for internal reflection), leaving two windows at said opposite facets for an incoming optical beam and an outgoing optical beam respectively, the windows being arranged to obtain an extended optical path of the optical beam through the crystal.

In the preferred embodiment of the device, it is adapted for altering the total length of the multi-segment trajectory, thereby enabling adjustment of the nonlinearity compensation, of the pulse shaping, and/or possibility of the signal monitoring. To this end, the device may have more than two optical ports for
incoming and outgoing beams, thus enabling selection and activation of any pair of such ports for a specific length of the trajectory. Alternatively or in addition, the device may be provided with collimators associated with the optical ports and serving for adjusting the incident angle of the light beam.

The device may be utilized for signal handling in a multi-channel transmission format, wherein each of the channels transmits an optical signal at a particular wavelength, said device being capable of Second Harmonic Generation with respect to the wavelengths of more than one channels of said format.

According to one particular embodiment, the pulse treatment device having the SHG property with respect to wavelengths of a number of the multiple optical channels is divided into a number of layers for respectively conveying there-through optical signals of the different optical channels. Ideally, the device serves all the multiple channels.

This embodiment is suitable for the WDM transmission format where the wavelengths of different optical channels are close to one another, (and provided that the common pulse treatment device performs its SHG property in response to at least a number of wavelengths of the respective multiple optical channels).

The layers may be separated either geometrically, or physically, say by optical gratings serving to prevent wavelengths of adjacent optical channels from passing via a particular layer. Actually, such physical separating means provide wavelength filtering.

The device is preferably integrated with an optical amplifier and is preferably placed immediately after said amplifier. The amplifier is usually utilized for adjusting the amplitude of the pulse applied to the device. In practice, the proposed device may form part of an optical network node.

According to an additional aspect of the invention, there is also provided a method for designing a signal handling device, which will be described, with the aid of drawings, in the detailed description of the invention.
Finally, there is proposed a suitable system for handling signals passing via optical fiber links from the point of pulse shaping, nonlinearity treatment and/or monitoring, the system comprising two or more signal handling devices as defined above, inserted in one or more optical fiber links and operative to perform pulse shaping, nonlinearity treatment and/or monitoring with respect to at least an optical pulse signal transmitted via one optical channel.

Adjustment of the systems' operation can be achieved by
a) reconfiguring the signal handling devices (selecting input-output ports, regulation of the collimators, etc.);
b) introducing additional devices or removing excessive devices;
c) changing distances between the devices and other elements of the link(s).

Further aspects and details of the invention will become apparent from the following description.

Brief description of the drawings.

The invention will further be described with reference to the attached non-limiting drawings, in which:

Fig. 1a (prior art) is a schematic illustration of a non-linear (SHG) element capable of producing a second harmonic from a fundamental harmonic of the applied optical signal.

Fig. 1b (prior art) schematically shows behavior of output powers of the fundamental harmonic and the second harmonic signals versus the propagation length in the SHG element.

Fig. 2a schematically illustrates effective results of the pulse shaping function of the SHG device.

Fig. 2b schematically illustrates counter-effective results of the pulse shaping function of the SHG device.
Fig. 3 shows several graphs obtained by mathematical simulation and demonstrating dependence of the shortest optical path in the SHG crystal on its mismatch coefficient q.

Figs 4 illustrates graphs obtained by mathematical simulation and characterizing the pulse shaping ability of SHG elements with different values of q.

Fig. 5 schematically shows mathematically obtained graphs of nonlinearity induced by the SHG element, in cases of the positive and the negative Kerr coefficients, respectively.

Figs. 6a and 6b schematically illustrate the proposed principle of monitoring an incoming optical signal using a second harmonic generated by an SHG element.

Fig. 7 schematically illustrates one embodiment of the signal handling device according to the invention.

Fig. 8 schematically illustrates another embodiment of the device.

Figs. 9a, 9b illustrate yet another embodiment of the signal handling device suitable for use in multi-channel transmission systems.

Fig. 10 is a schematic exemplary illustration of the proposed method and system for handling optical signals by compensation of non-linearity, monitoring and/or pulse shaping in optical fiber communication links.

Fig. 11 schematically illustrates another embodiment of the system according to the invention, for a multi-channel transmission format.

Detailed description of the invention

In the frame of the present application, three techniques using a novel so-called signal handling device are described, which have been proposed by the Inventors.

On one hand, the Inventors propose a method for regulating nonlinearity, usually and preferably – for compensation of a regular positive
nonlinearity in an optical communication link by introducing in said link one or more so-called pulse treatment devices capable of producing an artificial negative nonlinearity for an optical signal passing there-through.

The communication link is an optical fiber link serving for transmitting there-through one or more optical signals using, respective, one or more optical wavelengths.

Examples of the above-mentioned pulse treatment devices can be found in the following non-exhaustive list comprising: a nonlinear optical crystal, a poled polymer fiber, and possibly a semiconductor wave guide. Preferably, regulation of the non-linearity is provided periodically, when the devices are inserted at a distance from one another, said distances being spanned by the optical fiber. However, the regulation can be non-periodic, i.e. the device(s) may of course be placed at a particular point of the link, and several (n) samples of the nonlinear crystal can be stuck together, thereby achieving the n-fold regulation (preferably, compensation) effect.

The non-linear optical crystals (for example, the presently available KTP, KDP, BBO or the like) are such capable of receiving a light beam at the fundamental harmonic and producing there-inside the second-harmonic light beam. For the sake of simplicity and in the frame of the present description, these crystals will be called Second Harmonic Generation crystals, or SHG crystals.

It is known that polymer fibers, if subjected to uniform poling, acquire the property similar to that of the above-mentioned crystals, i.e., the capability of producing the second harmonic when conducting the fundamental-harmonic light beam.

Both in the nonlinear crystals, and in the polymer fibers, the property of SGH (second harmonic generation) is capable to induce the negative sign of the effective nonlinearity produced by the device.

The semiconductor waveguides at particular conditions (when the carrier frequency of the light signal is close to the half-band of the
semiconductor material) also may produce the negative nonlinearity, though this effect is based on different physical principles.

It is known to the specialists that the second harmonic generation in quadratically nonlinear media can be described by a system of two differential equations:

\[
\begin{align*}
    i \frac{dU}{dz} + U*V &= 0 \\
    2i \frac{dV}{dz} + \frac{1}{2} U^2 - q*V &= 0
\end{align*}
\]

(2)

Where: \(U(z)\) is a complex amplitude of the fundamental (first) harmonic of the light signal,

\(V(z)\) is a complex amplitude of the second harmonic of the light signal produced in the crystal,

\(z\) is the propagation distance for the light signal,

\(q\) is a so-called mismatch coefficient, or phase-velocity mismatch parameter, depending on the wavelength of the optical signal

\(i\) is the square root of \((-1)\),

\(*\) - is the symbol for the complex conjugation.

It is also known that the nonlinear phase shift \(\Delta \phi\) of the light beam at a fundamental harmonic emerging from the crystal is proportional to the following product:

\[
\Delta \phi = K_{\text{eff}} |U|^2
\]

(3)

where \(K_{\text{eff}}\) is the effective Kerr coefficient achieved in the crystal, and the FH field is taken at \(z=0\) (the input field).

Further, it is known that a very large value of the effective Kerr coefficient \((K_{\text{eff}})\) can be generated via a so-called cascading mechanism in the second-harmonic-generating optical crystals [see a review article by G.I. Stegeman,

Namely, it has been noticed that the value of \( K_{\text{eff}} \) in the non-linear (SHG) crystals is much larger than the natural Kerr coefficient of the crystal,

\[
|K_{\text{eff}}| \sim +10^4 * K,
\]

where \( K \) is the intrinsic Kerr coefficient.

The most important fact is that the gigantic Kerr coefficient \( K_{\text{eff}} \) induced by the cascading mechanism may have either positive or negative sign. As it follows from the system of equations (2), it can be readily controlled by means of the phase-velocity mismatch parameter \( q \). In turn, the latter parameter may be effectively controlled by means of the so-called quasi-phase-matching technique, which is based on a periodic poling of the optical crystal, see, for instance, a paper by O. Bang, C.B.Clausen, P.I.Christiansen, and L. Torner Engineering competing nonlinearities. Optics Letters, October 15, 1999, Vol.24, No.20. So, the sign of the cascading-induced effective Kerr coefficient \( K_{\text{eff}} \) may be made negative to produce the negative formal Kerr effect, which is necessary to compensate the ordinary positive Kerr effect accumulated in long fiber spans.

The above-mentioned estimate that the effective Kerr coefficient \( K_{\text{eff}} \) induced by the cascading may exceed the intrinsic Kerr coefficient \( K \) by up to four orders of magnitude implies that, for a 50 km long fiber span, the necessary compensating optical path in the second-harmonic-generating crystal must be approximately 5 m. Currently, it seems unrealistic to directly
implement the latter condition in an SHG medium, as the actual size of the presently available crystal samples (which have the cubic form) is limited by 5 cm (however, other samples may appear in practice in some time, if the proposed technology for the nonlinearity compensation is accepted by the industry).

Taking into account the presently available actual size of the crystals having the cubic form, a practical solution is to cover two opposite facets of the cubic sample by mirror surfaces. Using reflections of the beam from the mirrors, it is possible to arrange a multi-pass transmission of the optical beam through the crystal. According to the above estimate, the actual number of the passes must approximately be 100, implying the separation ~ 0.5 mm between adjacent trajectories, which is very easy to implement.

To make this device most efficient and economical, it should be integrated with amplifiers periodically placed in the fiber communication line. Preferably, the second-harmonic-generating crystal device must be placed immediately after the amplifier, to maximize the effect provided by the device by means of using the largest input power possible.

An approximate straightforward calculation taking into account gradual attenuation of an optical signal in the free-propagation fiber span demonstrates that if the device is placed immediately after the amplifier, the necessary length of the “nonlinearity compensating” optical path can be additionally reduced by a factor of about 2.5. This result eventually implies that the incidence angle of the beam shuttling inside the mirror-covered second harmonic generating crystal, which has the size 5cm x 5cm, should be of about 1.5 degrees, which is fairly easy to implement.

For a multi-channel transmission, such as in WDM systems, one nonlinear crystal can be used for non-linear regulation/compensation of a number of WDM channels. Many optical channels having different wavelengths can propagate in the non-linearity compensating device along different trajectories arranged in different layers of the device. Generally, the
mismatch coefficient \( q \) is different for the different wavelengths (i.e., \( q \) is subject to chromatic dispersion), which, in principle, may be compensated by arranging slightly different incidence angles for the spatially separated beams carrying different channels through the SHG crystal, see above. In any case, if it is known in advance which channels will suffer from incomplete compensation of the nonlinearity, they can be used for transmitting less responsible information.

It has been noticed by the Inventors that the proposed device, being effective in regulating/compensating the nonlinearity, successfully provides the pulse shaping as well. In other words, the pulse shaping of an optical pulse signal can be achieved by passing it through the above-mentioned SHG device, which may be a small optical crystal or, in principle, also a poled piece of a polymer fiber. It is assumed that the carrier frequency of the optical signal coincides with the frequency of the fundamental harmonic (FH) involved into the parametric energy conversion inside the SHG module. Parameters of the module (first of all, the optical path of the beam propagation inside the module) can be easily selected so that the peak power of the given input signal exactly or approximately corresponds to the complete conversion cascade: \( \text{FH} \rightarrow \text{SH} \rightarrow \text{FH} \), so that the portion of the signal around its center will be passed by the module with a very little share of the power lost to the generation of a residual portion of the second harmonic (SH). However, for portions of the same signal corresponding to smaller local values of the power, the actual propagation length in the module will be quite different from that corresponding to the complete cascade, hence, a considerable part of the energy will be lost by those portions (as the SH wave cannot propagate in the optical communication fiber). This simple mechanism can effectively chop off wings of a smooth pulse, making its shape essentially closer to the rectangular one.

Of course, the proposed shaping mechanism gives rise to extra energy losses, which should be compensated by an increase of the gain provided by the optical amplifiers installed into the link. Due to this, the preferred arrangement
of the link is that with the pulse-treatment device placed immediately after the amplifier, which will make it possible to reduce the propagation length of the signal inside the device, necessary for the completion of the nonlinear (power-dependent) conversion cascade.

However, estimates show that, even in such a configuration, the FH propagation length necessary for pulse shaping at a particular input power amplitude, which can be achieved with available SHG crystals, is much larger than the possible largest size of the crystal. Again the same solution as that proposed above for the nonlinearity compensation may resolve the problem: one may pass the signal through the crystal many times. In other words, both for the nonlinearity compensation and for the pulse shaping, the Inventors propose the configuration with the SHG element (actually, the crystal) covered by reflecting mirrors on its front and back facets, leaving two narrow windows, to be used as the entrance for an input signal and the exit for an output one.

Actually, the device described above is a unit that can be easily inserted at a suitable point into an optical link. For example, it can be integrated into a network node, which usually comprises amplifiers and devices for compensating other undesired effects (for instance, optical filters).

The drawings that are referred to below illustrate the most preferred embodiment of the invention according to which the pulse-treatment device is based on the SHG optical crystal.

An Inventors' theoretical article "Shaping NRZ pulses and suppression of the inter-symbol interference by a second harmonic generating module" (on 16 October, 2001 accepted for publication in Optics Communications, published by North Holland Physics, POBox 2759, 1000 CT Amsterdam, The Netherlands), which describes further technical details, is incorporated herein by reference. A copy of the text of the article is attached hereto as a supplement.

Further, the Inventors propose using the signal treatment device comprising an SHG element for monitoring an incoming signal applied to the
device at the fundamental harmonic (FH), by means of monitoring and further processing an outgoing signal at the second harmonic (SH). By selecting an internal optical path in the signal treatment device, a suitable SH signal can be obtained which enables monitoring thereof and judging on the incoming signal, including determining a number of its parameters. If performed by one and the same device, the monitoring can be best combined with the nonlinearity treatment/compensation.

In Fig. 1a, the optical non-linear crystal is marked 10, the incoming optical signal carried by the fundamental harmonic U(FH) is marked 12, the optical axis “z” of the crystal is marked 14. The crystal produces an output fundamental harmonic U’ signal (16) and also an output second harmonic signal V (18). The behavior of the output power in the fundamental harmonic (FH) U’ and second harmonic (SH) V vs. the propagation length of the signal in the crystal is shown in Fig. 1b.

For the effects of pulse shaping and nonlinearity treatment, the invention puts an emphasis on obtaining from the crystal the FH signal U’, which is always characterized by a particular sign of the cascading-induced effective Kerr coefficient. The character of the nonlinearity induced by the crystal in case of the positive or the negative effective Kerr coefficient is schematically shown in Fig. 5.

The above effects are based upon the output FH signal U’, while the effect of monitoring utilizes the output SH signal (see Figs 6a,b,c). To obtain the output FH signal upon the complete cascading process, the length “z” of the required optical path in the crystal (along the axis z) can be predicted using the system of equations (2). It is known and schematically shown in Fig. 1b that the FH output periodically increases and decreases, depending on the length of the optical path in the crystal (see points Z’ and Z” of maxima of the FH output). Therefore, for obtaining the effects of pulse shaping and the nonlinearity treatment, the crystal should provide for such a length of the
optical path which ensures the maximum power output at FH. Additional conditions will be explained with the reference to Figs. 2a, and 2b.

For designing the device suitable for the nonlinearity compensation, the sign of the Kerr effect created in the crystal should be negative. For designing the device mainly intended for pulse shaping or monitoring, the sign of the induced Kerr effect is unimportant, though should be taken into account in the network calculation. It is to be emphasized that the single nonlinear crystal with the negative sign of the Kerr effect can be designed and utilized for any of the proposed purposes.

Figs. 2a and 2b illustrate how the pulse shaping mechanism depends on the optical path (propagation length) of the fundamental harmonic in the SHG element.

It has been found and shown by the Inventors that if an optical pulse signal 15 having a Gaussian shape with the amplitude $P_{\text{max}}$ is applied to an SHG device 10 as its Fundamental Harmonic, there can be found a shortest optical path $Z'$ in the device, corresponding to the first maximum of the FH output power signal, upon passing which the pulse leaves the SHG device without loss of its peak power, while the slopes of the pulse are transmitted with losses. The obtained re-shaped pulse, being closer to a rectangular pulse, is marked 17 in Fig. 2a.

When the optical path essentially deviates from the shortest path $Z'$ and approaches a path $Z''$ corresponding to the second maximum of the FH output power signal, the shape of the obtained pulse will become distorted and may finally acquire the form close to 19 schematically shown in Fig. 2b by a solid line. If the optical path is further increased and attains the third maximum, the output pulse shape might assume an oak-leaf shape (shown by the wavy line). Therefore, for obtaining the pulse-shaping effect from the proposed signal handling device, the use of the shortest optical path is preferred. Other maxima of the FH output energy (second, third, etc.) and optical paths associated therewith can be used for the nonlinearity compensation but seem impractical
for the pulse shaping requirement due to severe distortion of the outgoing pulse.

Figs 3, 4 and 5 illustrate mathematically obtained graphs characterizing various SHG elements, which graphs can be used for the design of the signal handling device according to the invention. In this particular example, we will describe designing the device suitable for pulse shaping and nonlinearity treatment.

To practically determine “the shortest optical path” or the shortest propagation length in a particular pulse-treatment device preferred for the pulse shaping, the following steps can be performed.

Since each particular SHG element is characterized by its two intrinsic parameters – the nonlinearity coefficient $\gamma$ and the mismatch $q$ (which, in principle, depend on the carrier wavelength), a graph of the FH-SH-FH cascaded generation can be drawn for the particular element and the specific FH wavelength (Fig.3 shows a number of curves for various values of the mismatch coefficient $q$). Each particular graph is drawn for a particular value of the normalized dimensionless pulse power and a normalized, also dimensionless propagation distance and actually shows how the degree of transmission of the FH through the element depends on the propagation length.

The following equation proposed by the Inventors defines the normalized propagation length in the device in terms of the real propagation length and constitutes a so-called condition of optimum pulse reshaping:

$$Z' = (\gamma \sqrt{P_{\text{max}}}) Z_{\text{real}}$$  \hspace{1cm} (5)

where

$Z'$ is the normalized length of the optical path in the particular SHG element, at the point of first maximum of the transmitted FH power;

$\gamma$ is a nonlinearity coefficient known for the particular SHG element;

$P_{\text{max}}$ is the peak power of the pulse applied to the SHG element at FH;
$Z_{real}$ is the real optical path which the incoming optical beam should pass in the SHG element to satisfy the condition of the full transmission of the pulse's peak power.

The point showing at which optical path $Z'$ the first maximum of FH occurs can be found using the above graph drawn for the particular SHG element.

The obtained dimensionless value of $Z'$ is used to solve the equation numerically, and we obtain:

$$\frac{Z'}{\gamma} = \sqrt{P_{\text{max}}} * Z_{real}$$  \hspace{1cm} (6)

In other words, knowing $Z'$ and $\gamma$ for a selected SHG element and using the above equation, one may select a suitable proportion between the power of the amplitude of a real optical pulse applied to the SHG element and the real optical path which is to be passed by this real pulse in the element. The suitable proportion allows obtaining an outgoing pulse providing for the pulse shaping and/or regulation of nonlinearity.

Such a device may be designed either for handling preferably a single effect (say, pulse shaping), or for the pulse shaping simultaneously with the nonlinearity treatment.

It has further been shown by the Inventors that efficiency of the pulse shaping depends on the value of mismatch $q$ of the SHG crystal, namely - the smaller the mismatch $q$, the sharper the pulse shaping effect (Fig.4). In light of the above, for designing the pulse treatment device preferably intended for pulse shaping, SHG elements with small values of $q$ are to be selected.

To practically estimate the degree of positive or negative non-linear phase shift which is introduced by a particular SHG device, an additional graph can be drawn, to be considered together with the above-mentioned transmission graph. Actually, for the same values $\gamma$ and $q$ of the particular SHG element, and the same FH wavelength, we plot the phase-shift vs. the normalized
propagation length (Fig. 5). The point on the phase-shift plots 22 or 24 corresponding to the first maximum (at $Z'$) of the transmission graph 20 will indicate the degree of nonlinearity which may be introduced by the particular signal handling device to a fiber-optic link. Keeping in mind that the sign of the nonlinearity is either positive or negative as shown in Fig. 5 (the graphs 22 and 24 pertain to the positive and negative resulting Kerr effect, respectively), the device may serve for regulation the total nonlinearity in the optical link.

Based on the above, and according to yet another aspect of the invention, there is provided a method for designing a signal handling device for treating at least one effect from a list comprising nonlinearity and pulse distortion of an optical pulse if applied to the device at a particular wavelength, the method comprising:

selecting a Second Harmonic Generating (SHG) element for the device, sensitive to a fundamental harmonic (FH) defined by the particular wavelength and characterized by its physical parameters;

selecting, by a suitable calculation, at least one ratio between amplitude of the pulse to be applied to the pulse treatment device at said wavelength and an optical path to be passed in the device to ensure the maximum peak power of an outgoing pulse at the FH,

choosing input and output ports defining the selected optical path.

The last step preferably comprises designing the element with mirror surfaces so as to form between the input and output ports the necessary multi-segment trajectory resulting from one or more internal reflections from the mirror.

The need to have an extended (multi-segment) optical path is dictated by the fact that the optical path, ensuring the maximum peak power of the FH pulse outgoing the device, usually appears to excess practically available dimensions of the SHG element to be used in the device.

When designing/producing the device for the nonlinearity compensation of the optical signal of a particular wavelength of interest, the method must
ensure that the sign of the effective Kerr nonlinearity created by the obtained element for the particular wavelength of interest is negative.

When manufacturing the device, the effective Kerr coefficient to be induced in the crystal can be controlled by periodic poling of the said SHG optical crystal.

The device may be designed with a number of optional input/output ports and optical collimators, which enable adjusting the device, at the site, to changing conditions and requirements, for example to the monitoring feature.

Fig. 6a schematically illustrates how the signals handling device comprising an SHG element can be used for monitoring the incoming fundamental harmonic signal U at the wavelength $\lambda_1$ by monitoring the outgoing second harmonic signal V having the wavelength $1/2 \lambda_1$ and processing results of the monitoring. A monitoring filter is responsible for outputting a particular portion (say, 5% or more) of the SHG signal from the nonlinear element; a second harmonic signal processor (SHSP) provides required operations to refer the obtained signal to behavior of the optical signal on the fundamental harmonic (FH) and determine such parameters of the FH signal as its bit rate, BER (bit error rate), power of the FH signal, spectrum of the FH, etc. The processor can be operative to produce various informational messages and/or control commands based on results of the monitoring. Position of the monitoring filter with respect to the SHG element may not coincide with position of the FH output, i.e., the internal optical path selected for the monitoring may differ from that selected for transmitting the main, fundamental harmonic signal through the SHG element. Such an optional position of the monitoring filter is marked with a schematic box.

Fig. 6b illustrates how the phase of output power of the outgoing SH signal should be selected to obtain a non-zero power of the second harmonic output suitable for monitoring thereof. As has been explained above, phase of the power signal of the SH outgoing signals depends on the length of internal optical path of the incoming beam in the device. Therefore, to allow the
monitoring operation on the SH, though to ensure transmitting the initial pulse signal through the device and outputting thereof on the FH, the internal optical path is preferably selected so as not to produce an output power peak of the fundamental harmonic (FH), for example somewhere corresponding to points m1, m2, m3 shown in the drawing. Generally speaking, the second harmonic (SH) signal may be extracted from the device at an output port different from the port where the fundamental harmonic signal is obtained. In any case, it should be taken into account that the power extracted from the SHG element with the SH signal will result in reducing the power amplitude of the obtainable FH signal. Therefore, a SH signal may be probed for monitoring at an output port on the element corresponding to point m4 in the drawing, but with the aid of the monitoring filter which allows only a partial extraction thereof.

In the frame of a single device, the monitoring function can be performed either alone, or be preferably combined with the nonlinearity treatment function. The pulse shaping function, if also required, can be better obtained by designing a separate signal handling device though other combinations are possible.

Fig. 7 schematically shows a cross-section of one embodiment of the signal handling device, comprising an optical crystal adapted for forming a multi-pass (multi-segment) trajectory of the optical beam and suitable for regulating nonlinearity, pulse shaping and/or monitoring of optical signals. The optical crystal is, say, a KTP or BBO nonlinear crystal of the cubic form, which is coated by internal reflecting surfaces at two of its opposite facets. As known in the art per se, there are various ways of creating such reflecting surfaces. In Fig. 7 the crystal is provided with one input opening in the reflecting surface, via which the incoming optical pulse signal, which corresponds to the fundamental carrier harmonic in terms of the notation adopted in the mathematical model introduced above, enters the crystal. The crystal is preliminarily controlled (schematically shown as arrow 38) to adjust the sign and value of the effective Kerr coefficient produced by it. Suppose, the
negative Kerr coefficient has been ensured. In the crystal, owing to the reflecting surfaces, the light beam is forced to follow the multi-pass trajectory 35 for extending the optical path and comes out via an output window 36 as a modified signal U'. In the signal U', the earlier accumulated positive Kerr effect is compensated with the negative Kerr effect created by the crystal. As has been explained before, the trajectory can be made sufficiently long to provide for the value of the effective Kerr coefficient required for compensating the accumulated positive Kerr effect. The accumulated compensating phase shift is almost directly proportional to the length of the total optical path via the crystal. To obtain the phase shaping effect in addition to the nonlinearity compensation, this length should approximately correspond to the first propagation maximum of the fundamental harmonic. The total trajectory length, in turn, can be regulated by the incidence angle of the beam 39.

For calculation of the extended optical path required for the nonlinearity compensation, the system of equations (2) can be used and boundary conditions of reflection should be considered for taking into regard the phase shift appearing at the points of the beam reflection from the mirror surfaces. Additionally, for performing both the pulse shaping and the nonlinearity, the relation between the minimal propagation length and the power of the FH input amplitude should be taken into account.

It should be noted that for providing the monitoring function, the selected trajectory length should not correspond to a maximum of the fundamental harmonic (i.e., a minimum of the second harmonic).

The crystal 30 can be placed in a container, and the windows 34 and 36 can be provided with collimating lenses for focusing and adjusting the light beam.

Fig. 8 shows another modification 40 of the proposed device, where the non-linear optical crystal (shown in its cross section) is completely coated by a reflecting surface 42. Openings 44 and 46 in the mirror surface are equipped
with adjustable collimating lenses (schematically shown as boxes) being connected to optic fibers 43 and 45. Owing to the additional reflecting surface at the bottom facet of the crystal, the optical path of the beam 48 in the crystal can be twice as long in comparison with that shown in Fig. 7 (if the crystals are similar). Moreover, one or more optional windows 49 can be provided on the surfaces of the crystal. The trajectory length can be thus regulated by selecting a particular incidence angle and a particular pair of the windows between which the beam should be passed. In principle, such a device may also serve as a variable signal handling module. It can be adjusted for changing conditions and requirements, and thus serve for any of the three described options – pulse shaping, nonlinearity treatment and signal monitoring.

Figures 7 and 8 may successfully illustrate a signal handling device for the multi-channel optical transmission, too. In such a case (for example, in a WDM transmission system) the incoming light beam arriving from an optical fiber comprises a number of fundamental harmonics with respective wavelengths $\lambda_1, \lambda_2, \ldots \lambda_n$ (n optical channels). Having the same incident angle, the fundamental harmonics propagate in the crystal along almost a common trajectory. It should be taken into account that value of the Kerr effect produced in the crystal depends on the wavelength, so results of the required signal handling operations provided by the crystal might be different for different optical channels.

Figs. 9a and 9b, showing two mutually perpendicular cross-sections, illustrate another embodiment 50 of the signal handling device, specifically designed for the use in multi-channel transmission systems, such as WDM ones. The multiplexing and de-multiplexing units associated with it are marked 52 and 54. The embodiment 50 comprises an SHG crystal geometrically divided into a number of layers 56 (preferably parallel), wherein each layer serves as a separate SHG element intended for the nonlinearity regulation, pulse shaping and/or monitoring in a particular optical channel. The layers 56
of the crystal 50 and the channels 58 of the multi-channel format are in one-to-one correspondence.

In this embodiment, the crystal is provided with mirrors 60 positioned at two opposite facets thereof, to enable internal reflections of each incoming optical beam. The mirrors 60 are provided with a pair of windows 62, 64 at each of the layers, for serving the incoming optical beam and the outgoing optical beam of each particular optical channel. Since each optical beam propagates in its own spatial slot, it does not affect processes taking place in adjacent layers. An estimate shows that the thickness of each layer does not have to be larger than 1 mm.

However, each of the optical channels may comprise parasitic wavelengths differing from the fundamental harmonic. Also, such irrelevant wavelengths may enter the layers at the stage of passing the demultiplexed channels to the SHG crystal 50. To overcome that, the embodiment shown in Fig.s 9a, 9b may comprise SHG layers 56 separated from one another by any insulating interface (not shown), for example by interface based on gratings.

Each layer may perform one or more of the signal handling functions, depending on the internal optical path length selected for the optical beam of the particular channel and additional equipment (amplifiers, monitors, collimators, etc)

Fig. 10 schematically illustrates a system where more than one inventive devices (66 and 68 are shown) are periodically inserted into a fiber-optic link 70 to compensate the ordinary positive Kerr effect accumulated in long fiber spans, to shape the distorted pulses and to monitor the signal. Non-linear optical crystals are suitable for the purpose. Knowing that the cascading-induced effective Kerr coefficient ($K_{eff}$) in a relatively small SHG crystal may be very high, and knowing how to adjust the sign of the effective Kerr coefficient in the crystal, the problem can be solved. The procedure of checking the sign of the Kerr effect of the crystal is performed in advance, when manufacturing it. If the sign of the effective Kerr coefficient does not suit the
purpose it will be altered by means of periodical poling (the quasi-phase-matching technique). Eventually, the value of the effective Kerr coefficient can also be adjusted, using this procedure. After ensuring that the effective Kerr coefficient is negative (arrow 21 signifies the operation provided in advance), its value may be further adjusted to the given length of the fiber-optic span, the nonlinearity accumulated in which is to be compensated. The most preferred option is adjustment of the effective optical path of the light beam inside the devices 66 and 68 by arranging the multi-pass internal transmission as is shown in Fig. 7 or 8. An additional option is to insert more signal handling devices into the link 70.

Suppose, the nonlinear optical crystal 66 also performs the pulse shaping. Its internal optical path is adjusted up to the minimum optical path at which the FH power output reaches its first maximum. Knowing the peak power required for effective operation of the communication link, the corresponding minimum optical path in the crystal is to be matched accordingly and maintained.

Optical signal amplifiers 72 and 74, *inter alia*, are intended for adjustment of the peak power of the FH pulses incoming the device 66 and 68, respectively.

Suppose the device 68, in addition to the nonlinearity compensation, also performs monitoring of the second harmonic signal using a block 75 shown schematically and generally called a second harmonic monitoring processor (SHMP). For example, the block 75 may analyze the amplitude of the SH signal outputted from the crystal 68 and based on that adjust the gain of the amplifier 74. Alternatively or in addition, the block 75 can be made operative to analyze whether rectangularity of the pulses arriving to the device 68 is sufficient and to affect the amplifier 72 of the nonlinear element 66 for adjusting its pulse-shaping function. An additional output 77 of the block 75 is intended for forwarding the monitoring results to a management unit (not
shown) for the analysis, management, control and maintenance purposes (for example, the bit rate can be changed based on the BER measurement).

The nonlinear crystals 66 and 68 may physically form a part of network nodes marked 76 and 78. Preferably, the crystals are placed immediately after the optical amplifiers 72, 74 of the nodes.

Fig. 11 illustrates an exemplary embodiment of a multi-channel optical transmission system 80 utilizing the proposed signal handling devices of different types (i.e., designed to preferably perform one or more of the mentioned functions). In this case the system is a kind of OADM comprising multiplexing and de-multiplexing components for handling multiple channels in the WDM transmission format. Let the pulse treatment devices designed for nonlinearity compensation be marked “A”, those designed for pulse shaping be marked “B”, and those allowing the monitoring on the second harmonic signal be marked “C”. A number of optical channels with different wavelengths λ1, λ2, ...λn is transmitted over a transmission link 82. A signal handling device 84 of the type “A” can be inserted in the link 82 to preliminarily compensate nonlinearity accumulated in all the optical channels due properties of the optical fiber of the link. The optical signals are de-multiplexed by DMUX unit 86. One of the channels (λn) is dropped and then added, but before dropping to a customer, the nonlinearity accumulated in the optical signal is finely compensated by device 88. The device is of a combined “A” and “C” type which enables monitoring of the signal. In a case when the data signals in this channel follow at a relatively low bit-rate, no serious signal shaping is required. Other channels are treated both against the nonlinearity accumulation, and against the pulse distortion. For example, the optical signal passing via the λ1 channel is conveyed via an “A”-type device 90 and then, additionally, via a “B” type device 92. The optical signal of the λ2 signal is treated by a combined “A,B” type device 94 which provides reasonable treatment to these two effects. The restored signals of different channels, with the newly added and not yet
distorted signal \( \lambda_n \) are multiplexed by the MUX unit 98 for transmitting via the subsequent optical link 100.

Optical signals of other channels may be treated in an analogous manner or using the multi-layer embodiment 50 of the signal handling device shown in Figs 9a, 9b.

It should be emphasized that the above description of specific implementations of the invention is not limiting, and other embodiments of the invention may be proposed within the scope of the concept, and are to be considered a part of the invention.

For the purposes of this specification it will be clearly understood that the word "comprising" means "including but not limited to", and that the word "comprises" has a corresponding meaning.

It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.
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Pages 32 to 37 are claims pages, they come after the attachment, which is pages numbered 38 to 61.
Shaping NRZ pulses and suppression of the inter-symbol interference by a second-harmonic-generating module

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Abstract

A device that shapes fiber-optic pulses by passing them through a $\chi^{(2)}$ optical crystal is considered. The length of the propagation in the $\chi^{(2)}$ medium is selected so that the fundamental-harmonic (FH) transmission coefficient attains its maximum, which corresponds to a complete $\chi^{(2)}$ cascade, for the power equal to the peak power of the input pulse, whose carrier frequency coincides with the FH frequency in the $\chi^{(2)}$ process. Portions of the pulse which have smaller values of the power are attenuated, as the cascading is incomplete in them. An estimate, based on relevant values of the peak power for NRZ signals, shows that the necessary length of the propagation in the $\chi^{(2)}$ medium is $\sim 100$ times larger than the size of available $\chi^{(2)}$ crystals. To resolve the problem, a multi-pass configuration with mirrors is proposed. A modification of the scheme, which makes it possible to shape pulses in a multi-channel (WDM) system, without inducing crosstalk in the $\chi^{(2)}$ crystal, is also proposed. Simulations demonstrate that the shaper, combined with a linear amplifier, provides for stable propagation of pulses in a linear dispersive fiber link. The most essential result is obtained for pairs of pulses: it is found that they co-propagate without developing an appreciable inter-symbol interference (ISI), provided that the initial separation between them exceeds a certain threshold value, which is found as a function of an effective mismatch $q$ of the $\chi^{(2)}$ unit. The function has two minima, at $q > 0$ and $q < 0$, suggesting a choice of an optimum operation regime.
1 Introduction

Despite a great deal of current interest to soliton-based return-to-zero formats of data transmission in fiber-optic communication links, the existing networks use a simpler non-return-to-zero (NRZ) format [1]. In an idealized fiber-optic link, where both the Kerr nonlinearity and group-velocity dispersion (GVD) may be neglected, a bit of binary-coded data is represented by an optical pulse which has a rectangular shape, if the bit is 1, or by the absence of the pulse in the time slot allocated to a given bit, if the bit is 0.

In reality, the average value of GVD in the link can be made equal to zero by means of periodically installed dispersion-compensating fibers (or Bragg gratings) [2], and there also exist possibilities (although they are still far from practical implementation) of periodic compensation of nonlinearity [3, 4, 5]. In any event, the GVD and nonlinearity shape a 1-pulse into a smoothed signal, which is usually close to a Gaussian.

The deviation of the signals in the NRZ transmission format from the ideal rectangular form gives rise to problems produced by overlapping of the pulses between themselves through their “tails”. A known problem of that kind is the inter-symbol interference (ISI) in bit strings ...101..., ...1001..., and so on. In these strings, the hiatus corresponding to one or more “zeros” between two (or more) “ones” is partly filled by tails generated by the “ones”. In fact, overlapping between the tails generates a local maximum of the field in the center of the slot reserved for the “zero(s)”. Such corrupted strings may, eventually, give rise to errors in the data transmission, hence ISI suppression is an important issue (see, original works and a textbook). A partial solution is provided by the above-mentioned dispersion compensation, which makes it possible to periodically undo the dispersion-induced spreading-out of a pulse. Nevertheless, consideration of other approaches to this problem, and, more generally, the problem of shaping NRZ pulses are quite relevant.

The objective of this work is to propose pulse shaping by means of periodically passing the pulse through a second-harmonic-generating (SHG, or $\chi^{(2)}$) device, which may be a small-size optical crystal or a poled piece of a polymer fiber. It is assumed that the carrier frequency of the optical signal coincides with the frequency of the fundamental harmonic (FH) involved in the parametric energy conversion inside the SHG module. Parameters of the module (first of all, the length of the light propagation inside of it) can be easily selected so that the peak power of a given input signal corresponds to the complete conversion cascade: FH $\rightarrow$ SH $\rightarrow$ FH, so that the portion of the signal pulse around its center passes the module with very little energy lost to the generation of a residual SH (second-harmonic) wave. However, for portions of the same signal corresponding to smaller local values of the power, the same propagation length in the SHG module is essentially different from the value corresponding to the complete cascade, hence, a considerable part of the energy will be lost by those portions (as the SH wave cannot propagate in the system's fiber), see Fig. 4 below. This simple mechanism can chop off wings of a smooth pulse, making it closer to the rectangular one. While for a single pulse the application of this
shaping mechanism is obvious, and was, as a matter of fact, discussed in some forms before [8, 9], in this work it will be shown that this reshaping tool is most efficient for the suppression of the above-mentioned ISI effect, when a two-pulse configuration is periodically reshaped. We note, parenthetically, that the generated SH wave component, which is to be lost in the output signal, can actually be used for in-line monitoring of the propagating signals.

The shaping procedure gives rise to extra energy losses (on top of the light attenuation in the fiber link), which can be compensated by an increase in the gain provided by the optical amplifiers installed in the link. In fact, the optimum arrangement is that with the SHG shaping module placed immediately after the amplifier, which will make it possible to reduce the propagation length of the signal inside the module, necessary for the completion of the nonlinear conversion cascade.

An estimate (see details below) shows that, even in such a configuration, the necessary propagation length, which can be achieved with available SHG crystals, is much larger than the size of available samples. To resolve the problem, we propose to pass the signal through the crystal many times, covering its front and back facets by mirrors, as is schematically shown in Fig. 3(a) below.

The situation of real importance to applications is that with a multi-channel WDM (wavelength-division-multiplexed) system, using several dozens different wavelengths inside one fiber [1]. We show (see Fig. 3(b)) that pulses belonging to different channels in the WDM system can be shaped by the single SHG crystal module separately, without inducing any crosstalk between them.

The paper is organized as follows. In section 2 we introduce a model of the SHG shaping module based on well-known SHG equations. We then display results of straightforward numerical simulations of these equations, which are necessary to define the transformation of the pulse's amplitude and phase profiles. In section 3, we display numerical results showing stable propagation of an initially Gaussian pulse in a linear dispersive fiber link with periodically installed shapers. In section 4, the most important problem is considered: the co-propagation of two Gaussian pulses initially separated by some temporal delay \( T \). Simulations demonstrate that the shaper can suppress the ISI effect, which is the central issue considered in this work. We conclude that there is a critical value \( T_c \) of the initial temporal separation \( T \), such that stable ISI-free copropagation of the pulses is supported by the periodic shaping if \( T > T_c \). The only free parameter of the shaping unit being mismatch \( q \) controlling the \( x(2) \) energy conversion, \( T_c \) is a function of \( q \). A result is that the dependence \( T_c(q) \) has two well-pronounced minima, one at \( q > 0 \), and one at \( q < 0 \). Since minimization of the temporal slot's width allocated to the bit-carrying pulse is a problem of fundamental importance for enhancing the bit-rate capacity of the fiber link, one should select the operational parameters of the proposed NRZ system with \( q \) close to a value providing for the smallest critical separation.
2 The shaping SHG unit

Equations describing the evolution of amplitudes \( u(\zeta) \) and \( v(\zeta) \) of the FH and SH fields coupled by the SHG process are well known [8, 10]. In a renormalized form, they are

\[
\begin{align*}
\frac{d}{d\zeta} i^2 u + 2u^* v &= 0, \\
\frac{d}{d\zeta} i^2 u + \frac{1}{2} u^2 - \beta u &= 0,
\end{align*}
\]

where \( \zeta \) is the distance passed by the beam in the SHG medium, the asterisk stands for the complex conjugation, and the real parameter \( \beta \), which may be positive or negative, measures an effective mismatch in the quadratic interaction between the FH and SH waves. If the light propagation in the material is characterized by the dispersion relation \( k(\omega) \), the mismatch is defined as

\[
\beta = 2k(\omega) - k(2\omega).
\]

The exact matching, at which the SHG process is strongest, corresponds to the point \( 2k(\omega) = k(2\omega) \).

We notice that Eqs. (1) and (2) ignore walk-off (group-velocity mismatch between the FH and SH waves) terms, which, generally speaking, should also be taken into regard [8, 10] (they may give rise, for instance, to the walking solitons in a dispersive SHG medium [11]). In the case of interest for the applications considered in this work, when the pulses' dispersion length is incomparably larger than the propagation length in the SHG crystal, the walk-off terms are negligible indeed. Nevertheless, we will need to add a condition of the group-velocity match between the FH and SH waves for a different reason, viz., the necessity to equalize the mismatch in different channels in the WDM scheme, see below.

Equations (1) and (2) can be simplified by representing the fields in the form

\[
\begin{align*}
u &= \sqrt{p} \cos \theta \cdot \exp \left( \frac{i}{2} (\phi + \psi) \right), \\
v &= (\sqrt{p}/2) \sin \theta \cdot \exp \left( i (\phi - \psi) \right),
\end{align*}
\]

where the angle \( \theta \) characterizes the distribution of the power between the harmonics,

\[
p \equiv |u|^2 + 4|v|^2
\]

represents the net power of the light signal, and \( \phi \) and \( \psi \) are, respectively, their overall and relative phases. A straightforward consequence of Eqs. (1) and (2) is the conservation of the net power, \( dp/d\zeta = 0 \). Remaining evolution equations, following from the substitution of (4) and (5) into Eqs. (1) and (2), take the form

\[
\frac{d\theta}{d\zeta} = -\sqrt{p} \cos \theta \cdot \sin(2\psi),
\]
which are supplemented by a separate equation for the overall phase. The latter one can be combined with Eq. (8) to cast it into a more useful equation for the evolution of the net FH phase that will be necessary below,

\[ \frac{d\psi}{d\zeta} = \sqrt{\frac{2-3\cos^2\theta}{2\sin\theta}} \cdot \cos(2\psi) + \frac{1}{2}\theta, \]

(8)

Assuming that the input signal is fed into the SHG module at the FH frequency, Eqs. (7) and (8) are to be solved with initial conditions

\[ \theta(\zeta = 0) = 0, \quad \psi(\zeta = 0) = \pi/4. \]

(10)

In fact, the initial value of \( \psi \) is arbitrary, but it must be set equal to \( \pi/4 \) to prevent a formal unphysical singularity in Eq. (8), as it was shown in detail in the work [12] (in which the SHG module, which additionally included losses at FH and gain at SH, was used to design a nonlinear optical amplifier). Finally, solutions for \( \theta(\zeta) \) and \( \psi(\zeta) \) are to be inserted into the right-hand side of Eq. (9), by integration of which the FH phase \( \phi + \psi \) can be found as a function of \( \zeta \).

Note that the system of equations (7) and (8) can be derived from the Hamiltonian

\[ H = \frac{1}{4p} \sin \theta \left[ \sqrt{2p} \cos^2 \theta \cos(2\psi) - 2\beta \sin \theta \right]. \]

(11)

The Hamiltonian is a dynamical invariant, i.e., \( H = \text{const} \) represents an implicit form of a general solution to equations (7) and (8), which is a well-known fact [8]. However, to find an actual dependence \( \theta(\zeta) \) which will play a crucial role below, it is actually much easier to solve Eqs. (7) and (8) numerically, rather than to explicitly use the conservation of \( H \). Note also that Eqs. (7) and (8) admit evident rescaling,

\[ \sqrt{2p} \rightarrow z, \quad \beta/(2\sqrt{p}) \rightarrow q, \]

(12)

which casts Eqs. (7) and (8) into the form

\[ \frac{d\theta}{dz} = -\cos \theta \cdot \sin(2\psi), \]

(13)

\[ \frac{d\psi}{dz} = \frac{2-3\cos^2\theta}{2\sin\theta} \cdot \cos(2\psi) + q. \]

(14)

The rescaled equations, together with the initial conditions (10), contain the renormalized mismatch \( q \), defined in Eqs. (12), as the single control parameter.

In Fig. 1 we display results of numerical integration of the system (13) - (14) at different values of \( q \), in the form of \( \cos^2 \theta \) vs. \( z \). If the signal leaves the SHG module after having passed the distance \( z \) in it, then, according to Eqs. (4) and (6), \( \cos^2 \theta(z) \) is the ratio of the output power at FH, which will couple into the
system fiber, to the input power, i.e., the transmission coefficient induced by the SHG module (the share of the output power which remains in the SH wave is lost, as SH cannot propagate in the fiber).

Of special interest are maximum and minimum values that the transmission coefficient may assume. The maximum value is 1, as \( \cos^2 \theta = 1 \) at \( z = 0 \), and this value must repeat itself periodically, due to the periodic character of the dynamics in this conservative system. Further, it follows from Eqs. (13) and (14) that the relative phase \( \psi \) vanishes at the points where \( \cos^2 \theta \) attains its minimum. Then, equating the values of \( H \) at the maximum-transmission points, where \( \cos^2 \theta = 1 \), and at points where the transmission coefficient attains its minimum \((\cos^2 \theta)_{\text{min}}\), it is easy to find that

\[
(cos^2 \theta)_{\text{min}} = \frac{1}{2} q \left( \sqrt{4 + q^2} - q \right),
\]

which can be checked to be in complete agreement with the numerical results displayed in Fig. 1.

The propagation distance \( z_1 \) corresponding to the first maximum of the transmission coefficient (i.e., the period of the system's evolution) is shown in Fig. 2 as a function of \( q \). In what follows below, we consider the passage of a temporarily localized pulse through the SHG module. In this case, we set the propagation length \( z \) equal to \( z_1 \), realizing the power \( p \) in Eqs. (12) as the peak power \( p_{\text{max}} \) of a given input pulse. Due to this choice, a central part of the pulse, where the power is close to the peak value, will pass through the SHG module without losses. However, for portions of the pulse with values of the power smaller than \( P_{\text{max}} \), the effective propagation distance \( z \), corresponding to the same physical distance \( \zeta \) passed in the SHG medium, but normalized with a smaller value of \( p \) (see Eq. (12)), is smaller than \( z_1 \), hence the corresponding transmission coefficient \( \cos^2 \theta(z) \) is smaller than 1, see Fig. 1, which will give rise to the pulse shaping.

One can estimate the actual value of the physical propagation distance \( \zeta \) in an SHG medium necessary for the completion of the conversion cascade, which corresponds to the first maximum of the transmission coefficient. Taking values of the \( \chi^{(2)} \) nonlinearity coefficient known for standard SHG materials, such as KTP and others [8], and a value \( \sim 100 \) mW of the peak power for the pulse just after it has passed the amplifier, which is the maximum value relevant to the NRZ format of the data transmission, one concludes that the necessary length is on the order of several meters, while the actual size of available SHG crystals is limited to several centimeters [8, 4]. However, the effective propagation length can be made sufficiently large, using a configuration shown in Fig. 3(a): due to reflections from mirrors covering the back and front facets of the \( \chi^{(2)} \) crystal, the beam can pass the crystal many times before leaving it through the output window. In particular, if the above-mentioned estimate shows that the beam must pass the crystal, roughly, \( \sim 100 \) times, it is easy to see that the incidence angle of the incoming beam must be \( \sim 1^\circ \). In the practical design of this scheme, one should of course note that the phase matching in the anisotropic crystal medium may be quite sensitive to the beam's orientation, therefore the
small incidence angle may affect the value of the mismatch parameter $\beta$ in Eq. (2).

An aspect of the design of the shaping module which is crucially important for real applications is the necessity to shape pulses in many parallel WDM channels. As the results are quite sensitive to the exact value of the mismatch, see Figs. 1 and 2, the first problem is to (nearly) equalize values of the mismatch in all the channels. To this end, we note that Eq. (3) shows that, in the first approximation, a small change $\delta \omega$ of the carrying frequency gives rise to a mismatch change

$$\delta \beta \approx 2 \left[ V_{gr}^{-1}(2\omega) - V_{gr}^{-1}(\omega) \right] \cdot \delta \omega,$$

where $V_{gr}^{-1}(\omega) \equiv dk/d\omega$ is the inverse group velocity at the carrying frequency $\omega$, which is calculated as per the dispersion law $k = k(\omega)$. Thus, the difference between the values of the mismatch in the WDM channels does not take place (in the first approximation) if the group velocities of the FH and SH waves coincide, so that Eq. (16) yields $\delta \beta = 0$. Note that the (approximate) equality of the FH and SH group velocities is a common condition necessary for the formation of spatial solitons in $\chi^{(2)}$ media [8, 10]. In the present context, the same condition proves to be necessary for the mismatch equalizing.

If the signals belonging to different WDM channels are passed together through the $\chi^{(2)}$ crystal, another severe problem may be a nonlinear inter-channel crosstalk between pulses simultaneously passing the crystal. Obviously, exactly the same condition, $V_{gr}(2\omega) = V_{gr}(\omega)$, which is necessary to equalize the mismatch in the different channels, will also make the crosstalk especially strong. However, the crosstalk may be avoided if the channels are spatially separated, by means of some demultiplexing device placed before the $\chi^{(2)}$ crystal. After the passage of the crystal, the beams may be coupled back by a multiplexing device into one fiber core, as it is schematically shown in Fig. 3(b). In that case, different parallel layers of the crystal are used to handle different WDM channels (which implies that the panels (a) and (b) of Fig. 3 show, respectively, the side and top views of the proposed shaping unit). To secure full suppression of the crosstalk, the layers can be separated not only virtually, but also physically by means of thin insulating layers. As the size of the available monocrystalline cubic sample is a few cm, while the width of the layer allocated for one channel does not need to be more than 1 mm, a sufficiently large number of the WDM channels can be accommodated in the module.

3 Shaping a solitary pulse

3.1 Action of the shaping unit

The mechanism for the power-dependent attenuation of the portions of the pulse with $p < p_{\text{max}}$ outlined above is mitigated by the fact that the corresponding renormalized mismatch $q$ gets larger with the decrease of $p$, according to Eqs. (12). Indeed, Eq. (15) shows that, at least, the minimum value of the transmission coefficient monotonically increases with the increase of $q$. Nevertheless,
passing a pulse through the SHG module with \( z(p = p_{\text{max}}) = z_1 \) does reshape the incoming pulse into a more rectangular one. The shaping function of the module can be specified by a plot showing the FH transmission coefficient \( \cos^2 \theta(z) \) vs. the input power \( p \), at a fixed value of the physical propagation distance \( \zeta \). However, no separate plot is needed, as, with regard to the definition (12) of the renormalized propagation distance \( z \), Fig. 1 actually shows the dependence of \( \cos^2 \theta(z) \) vs. \( \sqrt{\beta} \) at a fixed value of \( \zeta \).

A more representative characteristic of the shaping is a picture showing the transformation of a standard input pulse under the action of the shaper. As a standard input, we take a Gaussian with the peak power \( p_{\text{max}} \) and temporal width \( T \),

\[
u(t = 0, t) = \sqrt{p_{\text{max}}} \exp \left( -\frac{t^2}{T^2} \right),
\]

where \( t \) is time. In view of the adjustment condition adopted above, \( z(p = p_{\text{max}}) = z_1 \), results can be presented in a form that does not depend on \( p_{\text{max}} \). Moreover, as the temporal variable does not appear above (as it was already mentioned, temporal effects are completely negligible within the crystal unit because the net distance \( \zeta \) of the passage through the crystal is a few meters, while the pulse’s dispersion length is \( \gtrsim 100 \) km), it is enough to display results for a single value of \( T \); they can be adjusted to other values of the temporal width by means of a straightforward rescaling.

An important fact is that, together with the transformation of the Gaussian’s shape proper (Fig. 4(a)), generation of the phase chirp, \( \delta = (\delta^2/\delta t^2)(\phi + \psi) \) (recall \( \phi + \psi \) is the net phase of the FH signal, see Eq. (4)) by the shaping unit also takes place; it is well known that the chirp strongly affects the pulse transmission in the fiber [1]. The generated chirp is shown, as a function of \( t \), in Fig. 4(b). In this connection, it is relevant to mention that, as it follows from an obvious symmetry of the underlying equations (1) and (2) and reduced equations (13) and (14), the shape transformation is exactly the same for values of the mismatch with opposite signs, \( q \) and \( -q \), while the chirp produced by the shaping unit reverses its sign if the sign of the mismatch is opposite.

To conclude this subsection, it is relevant to mention that using \( \chi^{(2)} \) nonlinear optical elements for pulse shaping is known in other contexts. The most frequently considered case is that when shaping of ultrashort pulses carried by the SH wave (rather than in the FH component, which is the difference from the case considered here) is helped by an SHG crystal included into a laser cavity, see, e.g., the work [9] and references therein.

### 3.2 Periodic shaping of the propagating pulse

As the next step, we simulated periodic action of the shaper, in the combination with a linear amplifier, which provides for a properly selected value of the gain, on a pulse propagating in a linear dispersive fiber link. The propagation in the fiber span is described by the linear Schrödinger equation,

\[
iu_x + \frac{1}{2}Du_{xx} = 0,
\]

where
where $r$ is, as usual, the reduced time, and $D$ is the dispersion coefficient [1]. We set $D > 0$, which corresponds to the anomalous group-velocity dispersion in the fiber. Intrinsic fiber losses are not taken into regard, as they are assumed to be compensated by the linear amplifier. A typical result is shown in Fig. 5, for a characteristic case when the span length is equal to the dispersion length of the pulse, $z_0 = DT^2/2$, where $T$ is the temporal width of the pulse (17).

These simulations suggest a conclusion that, in a broad interval of the values of the mismatch controlling the operation of the shaping unit, it is possible to select a value of the amplifier's gain that provides for fairly stable propagation of the periodically shaped pulse. Note that, strictly speaking, the dynamical regime considered here may be unstable, as the gain must compensate not only the intrinsic fiber losses, but also the additional losses incurred by the periodic action of the shaper, and the excess linear gain destabilizes the zero-solution background around the pulse. The absence of any apparent instability in our simulations can be explained by the fact that small perturbations around the pulse spread out, due to the presence of the dispersion, faster than they grow under the action of the excess gain. In fact, these stably propagating pulses are quite similar to (effectively) stable pulses which are known in nonlinear-optical models of the Ginzburg-Landau type based on the $\chi^{(2)}$ nonlinearity, which include losses, linear gain, and filtering [13] (filtering is absent in the present model).

4 Suppression of the inter-symbol interference

As it was explained in the Introduction, the ISI (inter-symbol interference) problem, i.e., gradual filling of the temporal gap between two neighboring NRZ pulses due to their spreading-out under the action of the dispersion (and, generally, nonlinearity) in the fiber is an issue of considerable interest to applications. The use of the shaping unit described above may provide for a natural tool for the suppression of ISI. This unit may find its most straightforward and practically feasible use if it is placed just before the receiver, or before each optoelectronic repeater, if they are present in the communication link, in order to clear up the gap between the two pulses, and thus to prevent a possible error. However, an interesting issue is also a possibility of stable co-propagation of two pulses, so that the temporal hiatus between them remains essentially empty. One may expect that there is a critical value $T_c$ of the initial time delay (separation) $T_0$ between the pulses, so that their co-propagation can be stably supported, in the above sense, if $T_0 > T_c$, while in the opposite case the ($T_0 < T_c$) the two pulses will, effectively, merge into one broad irregular pulse.

Direct numerical experiments similar to those reported in the previous section for the single pulse corroborate the existence of the critical separation. In Fig. 6(a), we display a typical example of the stable co-propagation of two pulses whose initial separation is close to the critical value. For comparison, in Fig. 6(b) we present the result of the propagation of the same initial configuration over the same distance in the fiber link without the shapers (and without
the extra gain compensating the shaper-induced losses), and in Fig. 6(c) the result is shown for a case when the initial separation is somewhat smaller than the critical value.

Data from a large number of simulations are collected in the form of the plot displayed in Fig. 7, which presents the most important result obtained in this work, viz., the critical separation $T_{cr}$ vs. the renormalized mismatch parameter (recall the renormalization, defined as per Eqs. (12), is always understood so that $p$ is the peak power of the initial pulse). A remarkable fact evident in this plot is the existence of two minimum values of the critical separation, which are slightly different for positive and negative values of the mismatch. The value of the mismatch which provides for the smallest critical separation should be selected for the best performance of the system, as it will provide for the largest bit-rate capacity possible.

The asymmetry between the results obtained for the negative and positive values of $q$ is explained by the difference in the sign of the chirp generated by the shaper, see Fig. 4(b). This shaper-induced chirp mixes with that generated by the linear dispersive fiber, which is always negative in the case of the anomalous dispersion ($D > 0$ in Eq. (18)). It is also noteworthy that the minimum of the critical separation as a function of the renormalized mismatch, found at $q \approx 0.1$ (see Fig. 7), is not too sharp, which secures tolerance of the system’s operation against inevitable fluctuations of the mismatch.

5 Concluding remarks

In this work, we have proposed a module shaping pulses in fiber-optic telecommunication links by passing them through a $\chi^{(2)}$ optical crystal. Direct numerical simulations have demonstrated that the $\chi^{(2)}$ shaper, acting in combination with the linear amplifier, supports stable propagation of solitary pulses, provided that the initial separation between them exceeds a certain critical value. The critical separation was found as a function of an effective mismatch controlling the operation of the $\chi^{(2)}$ unit, with two well-defined minimum values. A particular design of the shaping unit, that provides for the necessary length of the propagation in the $\chi^{(2)}$ material (which must necessarily be much longer than the size of available $\chi^{(2)}$ crystals), and secures the handling of a multi-channel WDM system, was proposed too.

Besides the scheme described in detail in this work, we also tried a more general one, in which the physical length of the propagation in the $\chi^{(2)}$ material, renormalized with the pulse’s peak power (see Eqs. (12)) corresponds, for a given mismatch, not exactly to the first-minimum propagation length (i.e., complete $\chi^{(2)}$ cascade), but is slightly larger. As it is suggested by Fig. 1, and is indeed corroborated by simulations, in this case of the “overshooting”, the top part of the shaped pulse is essentially closer to a rectangle than that in Fig. 4. However, further simulations demonstrate that this configuration, although it is also usable, does not improve the co-propagation of the pulse pair (the critical initial separation is not reduced).
An essential generalization of the fiber-link model studied in this work will be to include the nonlinearity of the fiber spans between the shaping modules, which will be considered elsewhere [15]. As is known, the fiber nonlinearity is not as crucially important for NRZ pulses as it is for solitons. Indeed, taking the standard values of the fiber's nonlinearity and attenuation parameters, 2 (km-W)^{-1} and 0.2 dB/km, respectively, one can easily conclude that the phase accumulation \((\Delta \phi)_{\text{nonlin}}\) in one fiber span due to the action of the nonlinearity becomes considerable \((\Delta \phi)_{\text{nonlin}} \gtrsim \pi\) for the post-amplifier pulse's peak power \(\sim 100 \text{ mW}\), which is the maximum value that may be relevant for the NRZ format (see above). Thus, the fiber nonlinearity may or (most probably) may not be directly important in the NRZ regime. Nevertheless, it is known that the addition of a relatively weak self-focusing nonlinearity to the linear anomalous dispersion of the fiber helps to stabilize the NRZ transmission regime, even in a case which is far from a soliton formation threshold, see, e.g., the work [14]. Therefore, we expect that results for the full model, that takes into regard both the \(\chi^{(2)}\) shapers and the fiber's \(\chi^{(3)}\) nonlinearity, may be quite interesting.

In the same connection, it is relevant to mention another interesting possibility, namely, that using an SEG module capable to generate an effective negative Kerr effect, which is a natural property of the \(\chi^{(2)}\) medium with the negative mismatch, can open way to periodically compensate the nonlinear self-phase modulation accumulating in the fiber spans [4]. Such a nonlinearity compensation may help to further stabilize the NRZ data transmission regime in nonlinear fiber-optic links [3]. This issue, however, cannot be considered without taking into regard the shaping induced by the \(\chi^{(3)}\) elements to be periodically inserted into the link. As it was mentioned above, this consideration will be a subject of a separate work.
References


6 Figure Captions

Fig. 1. A set of numerical solutions to Eqs. (13) and (14), shown in terms of \( \cos^2 \theta \) (the transmission coefficient for the fundamental-harmonic wave, see the text) vs. the renormalized distance \( z \) (defined in Eqs. (12)) of the propagation through the second-harmonic-generating medium, at different values of the renormalized mismatch \( q \).

Fig. 2. The renormalized propagation distance \( z_1 \), corresponding to the first maximum of the transmission coefficient \( \cos^2 \theta \) for the fundamental-harmonic wave, vs. the renormalized mismatch \( q \).

Fig. 3. (a) A configuration providing for the multiple passage of the optical signal through the second-harmonic-generating module (crystal). (b) A principal scheme for the parallel but mutually independent shaping of pulses belonging to different WDM channels. “Demux” and “Mux” are, respectively, the demultiplexing and multiplexing devices, which separate the channels in space, each being sent to its own layer inside the single SHG crystal, and then couple them back into one fiber core.

Fig. 4. (a) Transformation of the shape of the input Gaussian pulse (17) with the peak power \( P_{\text{max}} = 1 \) and width \( T = 100 \), which passes the shaping module whose parameters are adjusted so that the pulse’s peak power corresponds to the full transmission (i.e., complete cascading cycle). (b) The phase chirp generated by the shaper.

Fig. 5. The shape of the initially Gaussian pulse (17) which has passed 8 linear fiber spans, with modules consisting of the linear amplifier and shaper inserted between them. The final shape shown in this figure is a snapshot taken after the action of the last shaper. The value of the mismatch renormalized with the peak power of the initial pulse (see Eqs. (12)) is \( q = 0.1 \), and the length of the span is equal to the dispersion length of the pulse.

Fig. 6. (a) An example of a pair of pulses which remain in a stable well-separated state after having passed 5 system’s periods, each including a span of the dispersive linear fiber with the length equal to the dispersion length of the initial Gaussian pulse (17), linear amplifier, and the SHG shaping unit. The initial separation between the pulses, \( T_0 = 270 \) ps is close to the critical value, the mismatch renormalized with the peak power of the initial pulse as per Eqs. (12) is \( q = 0.1 \), and the length of the span is equal to the dispersion length of the pulse. (b) For comparison, the result of the propagation of the same initial configuration in a plain dispersive linear fiber link, which does not include the shaper and has the same net length, is shown. (c) The result of the propagation in the same model as in the case (a), but with the initial separation \( T_0 = 230 \) ps, which is slightly smaller than the critical value.

Fig. 7. The critical (minimum) separation between the pulses, necessary for their stable co-propagation, vs. the renormalized mismatch parameter, which is defined as per Eqs. (12), where \( p \) is the initial power of each pulse.
crystal transmission vs. propagation length for different values of the mismatch $q$

- $q = 0.01$
- $q = 0.10$
- $q = 1.00$

Fig. 1
Position of the first FH transmission maximum vs. mismatch
Mirrors

Demux

Mux
Fig 4a.
initial

after 8 spans
THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for handling an optical pulse signal by ensuring at least one operation from the following: pulse shaping, treatment of nonlinearity and monitoring, the method comprising steps:

   providing a signal handling device capable of performing a cascaded second harmonic generation (SHG) with respect to a particular fundamental harmonic (FH),

   selecting an optical path length in said signal handling device, suitable for performing at least one of said operations with respect to an incoming optical pulse signal carried by a wavelength defined by said particular fundamental harmonic (FH),

   conveying the incoming optical pulse signal carried by said wavelength along the selected optical path in said signal handling device,

   obtaining from said signal handling device at least one output optical pulse signal from a list comprising:

   an output optical pulse signal at the fundamental harmonic (FH), wherein the treatment of nonlinearity and/or the pulse shaping are performed,

   an output optical pulse signal at the second harmonic (SH) for further monitoring it and judging about said input optical pulse signal.

2. The method according to Claim 1, enabling the operation of nonlinearity treatment, wherein at the selecting step such an optical path length is selected for conveying the incoming optical pulse signal with a known amplitude via the signal handling device, that is substantially close to the length upon passing which the output optical pulse signal at the fundamental harmonic (FH) reaches the maximum peak power.

3. The method according to Claim 1, ensuring the operation of pulse shaping, wherein at the selecting step such an optical path length is selected for conveying the incoming optical pulse signal with a known amplitude via the signal handling device, that is substantially close to the shortest optical path...
length upon passing which the output optical pulse signal at the fundamental harmonic (FH) reaches the maximum peak power.

4. The method according to Claim 1, allowing for the monitoring operation, wherein the selecting step comprises selecting such an optical path length for conveying the incoming optical pulse signal via the signal handling device, that enables obtaining from said device the output optical pulse signal at the second harmonic (SH) with a non-zero peak power.

5. The method according to Claim 1, wherein the conveying is performed by passing the signal along a multi-segment trajectory in said device, thereby arranging an extended optical path.

6. The method according to Claim 5, wherein the conveying is performed via a multi-segment “zig-zag” trajectory by arranging one or more internal reflections in the signal handling device.

7. The method according to Claim 2, for nonlinearity compensation, further comprising a preliminary step of ensuring that the sign of the Kerr effect created by said device to said wavelength is negative.

8. The method according to Claim 1, for gradual handling of the optical signal in a fiber optic link, comprising an additional step of conveying the outgoing optical signal via a chain including at least one additional signal handling device, and wherein the devices in the chain are spanned by sections of the fiber optic link.

9. The method according to Claim 1, for handling optical pulse signals in a multi-channel transmission of optical data where each of the optical channels transmits a specific optical signal at a particular optical wavelength, comprising performing steps of Claim 1 with respect to each particular optical channel.

10. The method according to Claim 9, comprising conveying the optical pulse signals of different said optical channels via respective different said signal handling devices.
11. The method according to Claim 9, comprising conveying the optical pulse signals of different said optical channels via one and the same common signal handling device.

12. The method according to Claim 9, comprising selecting optical channels with better results of the signal handling for transmitting information having higher priority.

13. A device for handling an optical pulse signal from the point of at least one of the following operations: pulse shaping, treatment of nonlinearity and signal monitoring,

   the device being capable of performing a cascaded second harmonic
generation (SHG) with respect to a particular fundamental harmonic (FH),

   the device being characterized by such an optical path length selected
for an incoming optical pulse signal carried by a wavelength defined by said
particular fundamental harmonic (FH), that upon conveying said incoming
optical pulse signal along the selected optical path, the device enables
obtaining at least one output optical pulse signal from a list comprising:

   - an output optical pulse signal at the fundamental harmonic (FH),
     wherein the treatment of nonlinearity and/or the pulse shaping are
     performed,

   - an output optical pulse signal at the second harmonic (SH) suitable
     for further monitoring and judging about said input optical pulse
     signal.

14. The device according to Claim 32, and having the optical path length close to the shortest one upon passing which the outgoing FH optical pulse signal reaches the maximum peak power, thereby suitable for pulse shaping.

15. The device according to Claim 13, comprising a second-harmonic-
generating (SHG) element selected from a non-exhaustive list including: a
second harmonic generating (SHG) optical crystal and a second harmonic
generating (SHG) polymer fiber.
16. The device according to Claim 15, wherein said SHG element constitutes an SHG optical crystal selected from a non-exhaustive list comprising KTP, KDP and BBO.

17. A device for handling an optical pulse signal, if applied at a particular wavelength, from the point of at least one of the following operations: pulse shaping, treatment of nonlinearity and signal monitoring;

    the device comprising an SHG element for performing a cascaded Second Harmonic Generation with respect to a Fundamental Harmonic (FH) defined by said particular wavelength,

    said element being covered by mirror surfaces at least at its two opposite facets and leaving at least two windows at said opposite facets for an incoming optical beam and an outgoing optical beam respectively, the arrangement being such to create one or more internal reflections of the optical beam if passing between said two windows, thereby providing an extended internal optical path.

18. The device according to Claim 17, wherein said extended internal optical path has the length suitable for obtaining an outgoing optical pulse signal on the fundamental harmonic (FH) with a peak power close to maximum and/or an outgoing optical pulse signal on the second harmonic (SH) with a non-zero peak power.

19. The device according to Claim 18, wherein said extended internal optical path has substantially the shortest length upon passing which the outgoing FH optical pulse signal reaches the maximum peak power.

20. The device according to Claim 17, wherein the element has a cubic form and is covered at its two opposite facets by the mirror surfaces leaving two windows at said opposite facets for an incoming optical beam and an outgoing optical beam respectively, the windows being arranged to obtain an extended optical path of the optical beam through the element.
21. The device according to Claim 17, provided with more than two said windows, thereby enabling selection and activation of any pair of the windows for adjusting length of said internal optical path.

22. The device according to Claim 17, further provided with collimators associated with said windows and serving for adjusting the incident angle of the light beam.

23. The device according to Claim 17, adapted for signal handling in a multi-channel transmission format wherein multiple channels transmit optical signals at respective wavelengths differing from each other, said device being capable of Second Harmonic Generation (SHG) with respect to the wavelengths of more than one channels of said format.

24. The device according to Claim 23, wherein the pulse treatment device, being capable of SHG with respect to the wavelengths of a number of the multiple optical channels, is divided into the number of layers for respectively conveying there-through optical signals of said number of the multiple optical channels.

25. The device according to Claim 24, wherein the layers are separated from one another geometrically.

26. The device according to Claim 25, wherein the layers are separated from one another by wavelength filtering means.

27. The device according to Claim 17, integrated with an optical amplifier and placed immediately after said amplifier.

28. A system for handling optical signals passing via optical fiber links from the point of pulse shaping, nonlinearity treatment and/or monitoring, the system comprising two or more signal handling devices according to Claim 13 or 17, inserted in one or more optical fiber links and operative to perform pulse shaping, nonlinearity treatment and/or monitoring with respect to at least one optical pulse signal.

29. A method for designing a device for handling optical signals from the point of at least one operation from a list comprising nonlinearity treatment,
pulse shaping and monitoring of an optical pulse if applied to the device at a particular wavelength, the method comprising:

selecting a Second Harmonic Generating (SHG) element for the device, sensitive to a fundamental harmonic (FH) defined by the particular wavelength;

selecting, by a suitable calculation, at least one relation between amplitude of the pulse to be applied to the pulse-treatment device at said wavelength and an optical path to be passed in the device to ensure either the maximum output peak power of an outgoing pulse signal at the FH, or a non-zero peak output power of an outgoing pulse signal at the SH;

arranging for at least one input port and at least one output port defining at least one optical path of the selected relations.

30. The method according to Claim 29, comprising the design of the element with mirror surfaces so as to form between the input and output ports at least one multi-segment trajectory resulting from internal reflections in the element.

31. The method according to Claim 28 comprising, for effective pulse shaping, the selecting of the SHG element with smaller values of its mismatch parameter.

32. The device according to Claim 13, having the optical path length close to a path upon passing which the outgoing FH optical pulse signal reaches the maximum peak power, thereby suitable for treatment of nonlinearity.

33. The device according to Claim 13, having the optical path length enabling an output optical pulse signal at the Second Harmonic (SH) with a non-zero peak power, thereby suitable for signal monitoring.

Dated this 16th day of November 2001
LIGHTSCAPE NETWORKS LTD.
By their Patent Attorneys
GRIFFITH HACK
Fellows Institute of Patent and
Trade Mark Attorneys of Australia
FIG. 1A

FIG. 1B
Prnax in F

Prnux out

FIG. 2A

FIG. 2B
FIG. 3

\[ \frac{P_{\text{out}}}{P_{\text{max out}}} \]

\( q = 0.01 \)
\( q = 0.10 \)
\( q = 1.00 \)

NORMALIZED LENGTH \( Z \)
FIG. 4
FIG. 5
FIG. 6A

FIG. 6B

FIG. 7

FIG. 8