

NONLINEARITIES IN HIGH-BIT-RATE OPTICAL COMMUNICATIONS

USING NONLINEAR OPTICS FOR THE COMPENSATION OF SIGNAL DISTORTIONS

PAOLO MINZIONI, ILARIA CRISTIANI, VITTORIO DEGIORGIO

Department of Electronics, University of Pavia, Pavia, Italy

Nonlinear optics will have a double role in next-generation optical communications. On the one hand, nonlinear effects arising in the propagation of very short pulses inside optical fibers will give an important contribution to signal degradation, on the other hand, signal management and corrections of signal distortions will be likely based on the availability of integrated nonlinear optical devices.

1 Introduction

Optical-fiber communications are an essential tool for the every-day activity of a large part of humanity, because they support the whole long-distance data and voice traffic. Present links are based on wavelength division multiplexing (WDM), which means that, for example, 64 different wavelengths (also called “channels”), each transporting the information at a speed of 10 Gb/s, can travel in the same fiber, so that the data-rate capacity of a single optical fiber is generally larger than 0.5 Tb/s [1]. At the research level, in order to increase the capacity of future transmission systems, channels with a speed of 100 Gb/s (and beyond) are currently under investigation.

Recently developed optical fibers can transmit data channels with low attenuation over a bandwidth that extends from 1300 nm to 1600 nm and the optical processing devices are progressively increasing their capability to handle very high-bit-rate signals, thus opening the way to an efficient scaling of network resources. As optical technologies are continuously improving their performance, they offer the potential for a continued decrease in the energy consumption and “cost per bit” over what is currently achievable, so that the concept of “green photonics” is proposed in the more recent literature [2].

There exists a wide variety of proposals concerning nonlinear devices and photonic materials for optical-signal processing, in this article we confine the attention to optical phase conjugators and to their utilization in optical-communication systems for the compensation of signal distortions.

Very high-bit-rate data signals require shorter pulses, which implies that optical dispersion and nonlinear effects start to play a major role. When optical pulses as short as a few picoseconds propagate into a fiber, their temporal shape and spectrum is modified by several effects; in particular optical dispersion (pulse temporal broadening) and self-phase modulation due to the Kerr effect (frequency broadening) strongly deteriorate the signal, and thus it becomes extremely important to apply suitable compensation methods in

order to have an error rate in the signal decoding at the receiver as small as possible. At present, fiber dispersion is compensated optically, although post-detection electronic dispersion-compensation techniques are also being studied. On the other hand, signal distortions due to nonlinearity are generally left uncompensated and the only way to limit their impact on the system performance is either to keep nonlinearities as small as possible, or to deterministically exploit them for dispersion compensation in soliton-based transmission systems. Unfortunately this latter technique is generally not suitable for transmission at very high bit rates, so that the problem of compensating distortions due to nonlinear effects is still open.

The light-matter interactions involved in the processes of optical dispersion and Kerr nonlinearity are fully coherent (that is, phase preserving), so that they are reversible. The idea is the following: if we are able to operate at mid-path along the transmission line a time-inversion operation by performing the optical phase conjugation (OPC in the following) of the signal, we can compensate at the same time dispersion and nonlinearity, so that we can recover at the receiver the same signal initially generated by the transmitter [3]. This idea represents an extension of an earlier proposal that was only aimed at the compensation of optical-dispersion effects [4]. The proposed method is, in principle, able to fully compensate signal distortions, provided that noise is negligible. Indeed degradation due to noise cannot be fully compensated. The method, conceptually simple and elegant, was first proposed in a form appropriate only for an idealized optical-communication system, in which the power of the optical signal is uniform along the link. An important modification was introduced in ref. [5] in order to take into account the existence of distributed losses and lumped amplification in real links. An aspect that, in any case, would have limited the applicability of the method is that, until about ten years ago, no efficient OPC device operating at power levels compatible with optical-communication links was available.

In this article we describe recent activity aimed at developing an all-optical compensation method for both dispersive and nonlinear effects, based on the insertion along the link of an integrated nonlinear optical device that performs the OPC of the transmitted signal. The paper is organized as follows: in sect. 2 we recall the main effects occurring in the propagation of ultrashort laser pulses in single-mode optical fibers, in sect. 3 we describe the OPC effect and how it can be realized, in sect. 4 we present a schematic description of an optical-communication system, and we review recent experiments demonstrating the effectiveness of the proposed OPC compensation method. The last section is devoted to concluding remarks.

2 Pulse propagation in optical fibers

At the state of the art, in an optical-communication link the information is transmitted by means of digital amplitude modulation of the optical carrier. Recently, schemes based on a combination of phase modulation and polarization modulation have also attracted a significant interest, as they could allow increasing the data transmission capacity. Since, in the most common cases, the optical communication signal consists in a sequence of binary digits (bits) in the form of ultrashort optical pulses [1], it is useful to start the discussion by describing the main phenomena occurring during pulse propagation along an optical fiber.

When the laser was born, the existing fibers presented very large losses: typically the attenuation coefficient was of the order of 100 dB/km, that is, the pulse energy was reduced by a factor of 2 after 30 m. Charles K. Kao and coworkers were the first to promote the idea that the attenuation in optical fibers available at that time was caused by impurities, which could be removed, rather than by fundamental physical effects such as scattering. This discovery led to a significant decrease of fiber losses as fibers with attenuation as low as 0.15 dB/km are currently available (a pulse can travel 20 km before its energy is halved) and led Kao to the Nobel Prize in Physics in 2009. Moreover, the transmission systems' limitations due to optical-fiber attenuation were almost completely removed in the nineties thanks to the development of erbium-doped fiber amplifiers (EDFAs) for the compensation of fiber losses. By using EDFAs the optical signal (with a wavelength $\approx 1.55 \mu\text{m}$, corresponding to the minimum value of fiber attenuation coefficient) can be periodically re-amplified (typically by a factor of 100 or even more) directly in the optical domain.

An important requirement for fiber-optic high-bit-rate transmission systems is that the fiber has to be single-mode at the operating wavelength. In fact, if the optical fiber supports more than one propagation mode, say n modes, the power of the optical signal injected into the fiber will be distributed among the n modes. Since the group velocity is different for each mode, a single pulse at the input would produce at the receiver a series of n temporally separated pulses. This is clearly not acceptable in a high-performance communication system and hence the use of single-mode fibers in such a situation is compulsory. Intrinsically single-mode fibers have a small core-diameter, typically $8 \mu\text{m}$, so that even modest optical powers (e.g., 10 mW) give rise to high intensities ($\approx 20 \text{ kW cm}^{-2}$), leading to significant nonlinear effects.

In the general situation, the propagating optical field can be written as a function whose amplitude and phase are both time and space dependent. Since the signal bit rate is always much lower than the frequency of the optical carrier (by at least three orders of magnitude), it is possible to apply

the slowly varying envelope approximation, so that the electric field of the propagating light pulse can be described as the product of a sinusoidal carrier at the central frequency ω_0 multiplied by the transverse mode distribution $B(x,y)$ and by the complex-envelope function $A(z,t)$, which contains, encoded in its amplitude and phase modifications, the signal information:

$$(1) \quad E(x, y, z, t) = A(z, t)B(x, y)\exp [i (\beta z - \omega_0 t)],$$

where the z -axis coincides with the fiber axis, $B(x,y)$ is a Gaussian function representing the transverse distribution of the fundamental mode, ω_0 is the angular frequency of the laser beam, and β is the propagation constant. We call n_{eff} the ratio between the light velocity in vacuum and the group velocity (v_g) inside the fiber, $n_{eff} = c/v_g$. Since the optical mode is mainly concentrated in the fiber core but its tails extend into the fiber cladding, the value of n_{eff} is intermediate between the indices of refraction of core and cladding. In general n_{eff} , and hence β , are nonlinear functions of ω . We express β by a power series expansion around the central frequency ω_0 of the traveling optical signal:

$$(2) \quad \beta = \sum_{k=0}^{\infty} \frac{\beta_k}{k!} (\omega - \omega_0)^k,$$

$$\text{where } \beta_k = \frac{\partial^k \beta}{\partial \omega^k}.$$

The effect of optical dispersion on the pulse envelope is that of progressively increasing the pulse temporal width during propagation. In particular, the parameter β_2 , known as the group velocity dispersion (GVD) parameter, determines how much an optical pulse would broaden on propagation inside the fiber. In the case of a Gaussian pulse having a full-width-half-height duration Δt_0 , the duration Δt after traveling along a distance z inside the fiber is

$$(3) \quad \Delta t = \Delta t_0 \sqrt{1 + \left(\frac{z}{L_D}\right)^2},$$

where the dispersion length L_D is given by $L_D = \Delta t_0^2 / |\beta_2|$.

For a standard single-mode fiber $\beta_2 = -20 \text{ ps}^2 \text{ km}^{-1}$. If we take $\Delta t_0 = 10 \text{ ps}$, a common value for a 40 Gb/s transmission system, we find $L_D = 5 \text{ km}$. Considering that the length of optical-communication links can be of hundreds or even thousands of kilometers, and that the temporal separation between consecutive pulses in a 40 Gb/s system is only 25 ps, it is easy to understand that dispersion would produce at the receiver a devastating overlap of several bits, unless low- β_2 fibers are used, or some compensation scheme is adopted.

In the linear-propagation regime dispersion produces a frequency-dependent dephasing of the pulse spectral

components that, in the temporal domain, results in a phase term proportional to the square of time. This phenomenon is usually called chirp.

The compensation of the optical dispersion is based on the consideration that the pulse stretching is a deterministic and linear process that can be undone in any point of the transmission system by using an optical component, such as a dispersion-compensating fiber (DCF) or a chirped fiber Bragg grating, having a β_2 with an opposite sign with respect to that of the transmission fiber.

Another source of distortion for optical pulses propagating in a fiber transmission system is given by nonlinear optical effects. The response of any dielectric to an electromagnetic field becomes nonlinear if the field is sufficiently intense, and even though silica is not a highly nonlinear material, the high beam intensities and the long propagation lengths make nonlinear effects become relevant in the design of modern optical-communication systems. For the purpose of the present discussion the most important nonlinear effect is the optical Kerr effect, which consists in a linear dependence of the index of refraction n on the intensity I of the light beam:

$$(4) \quad n = n_0 + n_2 I,$$

where n_0 is the unperturbed index of refraction and n_2 is proportional to the third-order electric susceptibility of the material. In the case of silica, n_2 is about $3 \times 10^{-20} \text{ m}^2/\text{W}$. The optical pulse travelling over a fiber length L takes a nonlinear phase shift ϕ_{NL} that is time dependent because the intensity is time dependent:

$$(5) \quad \phi_{NL} = L \frac{2\pi}{\lambda} n_2 I(t).$$

The phenomenon described by eq. (5) is called self-phase modulation (SPM) since the phase shift is induced by the optical field itself. The effect of SPM is that of broadening the frequency spectrum of the propagating pulse. In turn, the increased spectral broadening enhances the temporal broadening due to the GVD and the interplay between SPM and the fiber dispersion may produce a significant change in the signal shape revealed at the receiver, thus introducing a signal distortion.

An additional effect leading to signal degradation is the quantum noise due to spontaneous emission in the EDFAs. In the case of phase-modulated systems, the presence of EDFAs gives rise also to a nonlinear phase noise, called Gordon-Mollenauer noise, due to the nonlinear interplay between the signal and the amplified spontaneous emission from the in-line amplifiers. Indeed amplified spontaneous emission adds linearly to the signal leading to an amplitude noise that is converted to phase noise through SPM [6].

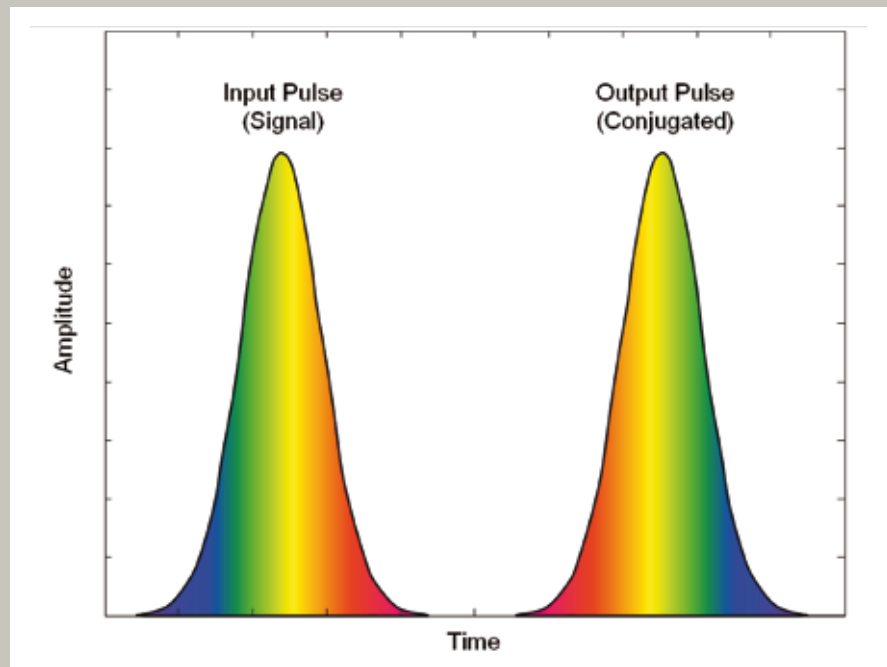


Fig. 1 If the instantaneous frequency of the input pulse changes linearly because of the chirp, the pulse produced by OPC shows an opposite chirp, thus appearing as “temporally inverted” with respect to the input signal.

3 Optical phase conjugation

The optical-phase-conjugation (OPC) process can be mathematically described as the conjugation of the complex envelope of the signal. This means that the signal produced at the output of an ideal optical phase conjugator is characterized by the same amplitude and real part of the incoming signal, and by an opposite sign of the imaginary part of the complex envelope. As a consequence, the produced output signal will have the same “temporal shape” of the incoming signal, but a “reversed” distribution in time of the spectral frequencies inside the pulse. Hence, when a linearly chirped pulse is considered, the chirp of the pulse at the OPC output has an opposite sign with respect to that of the input pulse. This “chirp-reversal” effect is the origin of the OPC capability to compensate the chromatic dispersion effect, as it produces an imaginary chirp term in the signal envelope. From a mathematical point of view this can be easily seen by comparing the complex-envelope A and its conjugated copy A^* :

$$(6) \quad A(t) = A_0 \exp \left[-(1 + iC) \frac{t^2}{\tau^2} \right] \Rightarrow A^*(t) = A_0 \left[-(1 - iC) \frac{t^2}{\tau^2} \right],$$

where C is the so-called chirp parameter.

Since only the even-order dispersion terms ($\beta_2, \beta_4, \beta_6, \dots$) produce a chirp that is described by an imaginary term in the complex-envelope description, it is quite straightforward to understand that the odd-order dispersion terms ($\beta_1, \beta_3, \beta_5, \dots$) cannot be compensated by means of OPC. Anyway since the β_1 term corresponds to a signal delay which does not introduce any distortion, being the same for all the signal frequencies, the first term that cannot be compensated by OPC is the one corresponding to the third-order dispersion (also called “dispersion-slope”) β_3 .

From a physical point of view, the effect of OPC can be described in the time domain as follows: OPC produces a pulse which is characterized by having an opposite chirp, and thus corresponding to a signal which is “temporally inverted” if compared with the original one, as schematically shown in [fig. 1](#). In particular, in [fig. 1](#) one can see that, when the leading

edge of the pulse (having an instantaneous frequency higher than the signal central frequency) is conjugated, it produces a part of the conjugated copy of the signal which has an instantaneous frequency lower than the central frequency of the conjugated signal.

We now shortly describe how the OPC effect can be experimentally produced. In order to generate the OPC of an optical signal one can use a four-wave-mixing (FWM) process in a third-order ($\chi^{(3)}$) nonlinear material [7] or a sequence of two second-order processes in a $\chi^{(2)}$ nonlinear material [8, 9]. The latter process can be anyway described by means of the “equivalent third-order susceptibility” $\chi_{\text{eq}}^{(3)}$.

Let us consider the four-wave-mixing process produced by the presence, inside a $\chi^{(3)}$ material, of two optical fields: a high-intensity continuous-wave field called “pump” (E_p) at frequency ω_p , and a “signal” (E_s) at frequency ω_s . The nonlinear interaction gives rise to a “conjugated-signal” (E_c), centered at the new frequency $\omega_c = 2\omega_p - \omega_s$, with a complex envelope that is given by the following equation:

$$(7) \quad E_c \propto E_p^2 E_s^* = A_p^2 A_s^* \exp(-2i\omega_p t) (+i\omega_s t) = A_c \exp[-i(2\omega_p - \omega_s) t] .$$

Equation (7) shows that the complex envelope of the conjugated signal (A_c), being A_p constant, is proportional to A_s^* . Moreover, comparing the original signal, given by $A_s \exp(-i\omega_s t)$, with the phase-conjugated signal, given by $A_c \exp[-i(2\omega_p - \omega_s) t]$ it is also evident that the signal produced by OPC has an optical spectrum that is symmetrical to that of the original signal with respect to the pump frequency, thus explaining also the use of the term “spectral inversion” to indicate the OPC operation.

The field described by eq. (7) is a wavelength-shifted replica of the input signal. The realization of an efficient all-optical wavelength conversion is, by itself, an important step toward the development of high-bit-rate WDM links, because the wavelength converter can substitute electronic equipment in the implementation of different functions, such as signal routing, collision management and path restoration [10].

Many distinct approaches have been followed for the realization of wavelength converters and optical phase conjugators based on FWM. Several groups have tested the utilization as the nonlinear material of semiconductor optical amplifiers (SOA) [11]. These devices, although showing non-negligible polarization dependence, are characterized by a high nonlinearity, a reasonable cost, and an extremely small footprint, that make them particularly interesting for the realization of all-optical signal processing structures. The nonlinear effects that can be used to produce a copy of the input signal inside a SOA at a different carrier frequency are mainly three: the cross-phase modulation, the cross-gain modulation and the four-wave mixing. Of these effects, the only one that allows producing also a phase-conjugated signal independent of the signal modulation format is FWM. In a SOA, the origin of the FWM effect is quite different from that of standard $\chi^{(3)}$ materials, because the nonlinearity comes from the combination of different electronic effects (both inter-band and intra-band). When two beams (the signal and the pump) with the same polarization state are sent into a SOA their beating produces a carrier density modulation, thus generating a spatial variation of the material refractive index. The produced spatial grating interacts with the pump beam yielding the generation of new frequency components, which correspond to the FWM products.

Another approach utilizes an optical fiber as the $\chi^{(3)}$ -medium. The use of a fiber-based optical phase conjugator is evidently interesting for its simplicity, low cost, and very low losses, but, because of the low value of the nonlinear coefficient, high pump powers and/or long fibers are needed, so that other competing nonlinear processes are triggered. Furthermore, the available conversion bandwidth is rather limited. The use of fibers as a medium to realize the OPC process was almost completely abandoned some years ago, until a revival happened in recent times thanks to the development of two new types of fibers presenting a much larger nonlinearity: bismuth-fibers and photonic-crystal fibers [12].

Fig. 2 On the left we show a schematic representation of the cascading technique, and on the right we illustrate the related spectrum of the interacting beams. An intense pump beam (red) produces, thanks to the substrate periodical poling, a SH beam (green), which is also responsible for the photorefractive effect. The SH beam interacts with the signal beam (blue) to produce an amplification of the signal, and the creation of a new "conjugate signal" (orange).

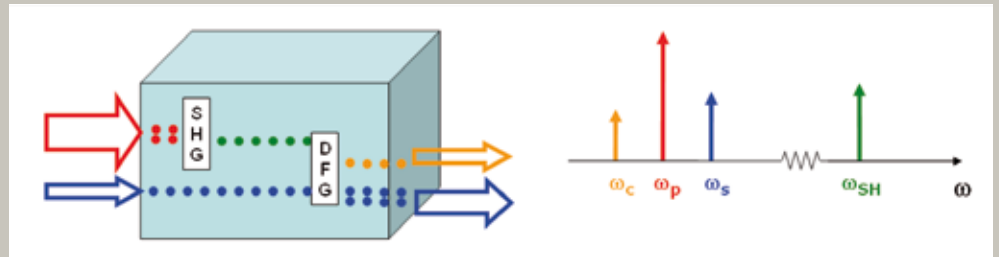


Fig. 3 Schematic representation of an OPC apparatus. The signal is amplified by an EDFA, filtered to remove the out-of-band amplified spontaneous emission and then coupled to a CW high-power pump beam emitted by a DFB laser. The two beams are sent to a PPLN waveguide where the OPC takes place and the output signal is then split into two beams. One beam is sent to an optical-spectrum analyzer (OSA), while the other is filtered, to remove the pump and the original signal, and then re-inserted in the transmission line.

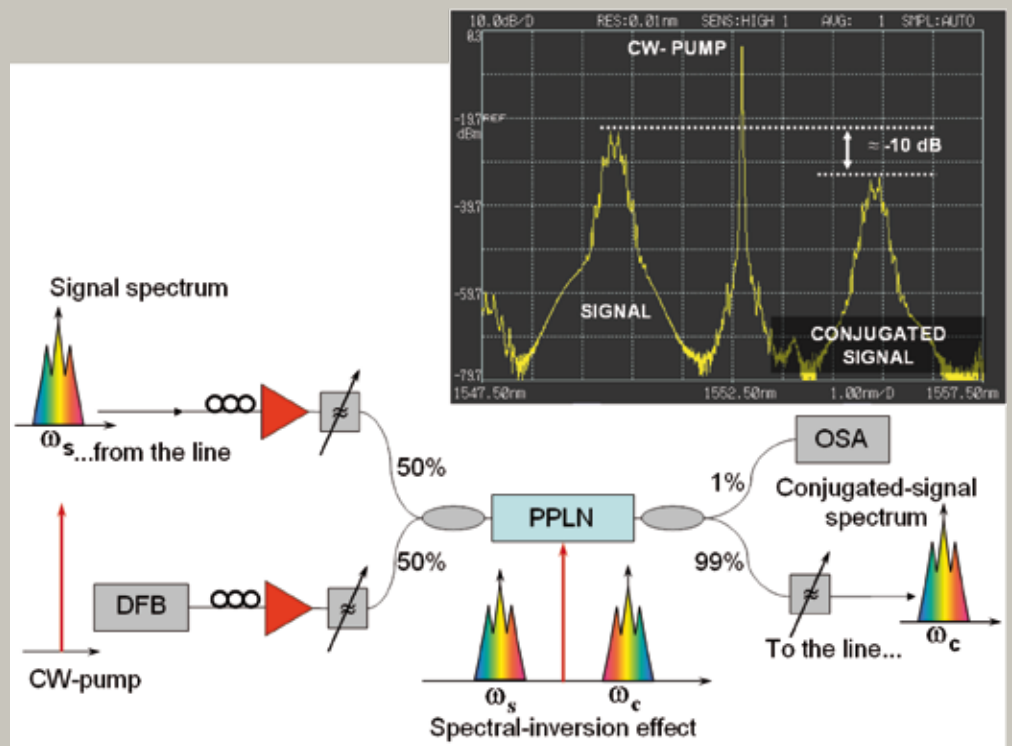
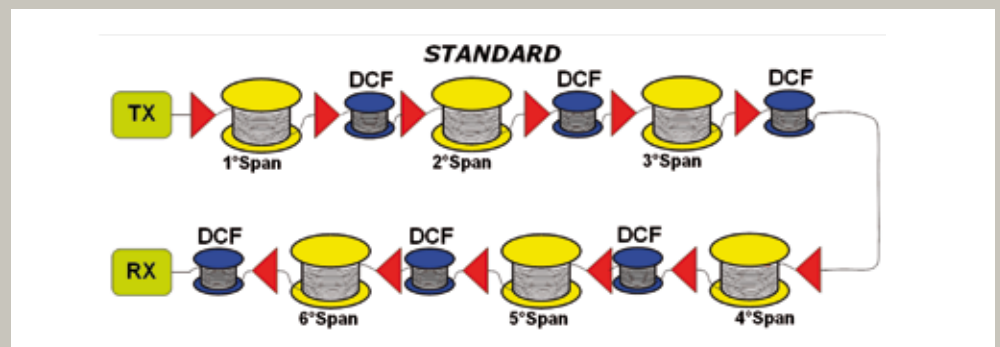


Fig. 4 Possible configuration of a state-of-the-art transmission link. The signal, produced at the transmitter (TX) propagates through different fiber spans (indicated by the large yellow spools). The position of EDFAs is indicated by red triangles. After each span the signal is first pre-amplified to reach a power level suitable for propagation in the DCF fiber (e.g. 0.1 – 0.5 mW), then it is launched in the DCF fiber spool for dispersion compensation, and it is finally re-amplified (to about 2 – 10 mW) for propagation in the following fiber span.



A recent research line is that of using silicon (Si) waveguides that, thanks to the extremely reduced size of the optical mode, allow producing significant nonlinear effects on extremely short propagation distances [13]. The advantage of a similar OPC device is given by the extreme compactness of the device and by the possibility to produce it in large volumes at low cost by exploiting the technology developed for microelectronics. The problem with Si waveguides is that linear and nonlinear losses may be quite large. In particular, two-photon absorption and, consequently, free-carrier absorption are present, so that the use of appropriate strategies to avoid their detrimental effects has to be considered.

At present, the most efficient OPC approach is represented by the cascading process in microstructured lithium niobate waveguides [8, 9]. A microstructured material in which the value of the nonlinear coefficient varies with a spatial periodicity Λ can exchange momentum with the propagating waves in multiples of the unit $2\pi/\Lambda$, so that, in principle, phase-matching can be achieved at any desired frequency by appropriately choosing the period Λ . Lithium niobate (LN) is an extremely interesting material for optical applications, as it has high electro-optic and nonlinear coefficients; moreover it is possible to obtain large crystals with very high optical quality, and the waveguide fabrication technologies have been thoroughly optimized in the past twenty years. Since the LN crystal is ferroelectric, it is possible to create inside the crystal a periodic alternation of up and down domains by applying a large electric field with appropriately patterned electrodes. This is what is called periodically poled lithium niobate (PPLN).

The “cascading” technique, which consists in the sequence of two $\chi^{(2)}$ nonlinear effects, is schematically shown in fig. 2.

The signal, at ω_s , is injected into the waveguide together with a pump beam at ω_p . As a first step, the second-harmonic generation (SHG) is used to produce a beam at frequency $\omega_{SH} = 2\omega_p$. SHG can be obtained with very high efficiency, assuming that the LN substrate is periodically poled (*i.e.* the orientation of the ferroelectric domains is periodically inverted) with an appropriate period. As a second step, a difference-frequency generation process is realized between the second-harmonic of the pump, and the signal at ω_s , thus producing a phase-conjugated signal at frequency $\omega_c = \omega_{SH} - \omega_s = 2\omega_p - \omega_s$. It should be stressed that, if the phase-matching condition for the SHG process is satisfied, the difference-frequency generation process is also approximately phase-matched and its bandwidth (generally well in excess of 40 nm) is limited only by the presence of the second-order dispersion. It can be shown that the overall process can be described by an equivalent $\chi_{eq}^{(3)}$ coefficient, given by the following equation (being L the waveguide

length and $\chi^{(2)}$ the second-order nonlinear susceptibility) [9]:

$$(8) \quad \chi_{eq}^{(3)} \propto \frac{L}{\lambda_p} |\chi^{(2)}|^2 .$$

Considering that it is possible to fabricate high-quality PPLN devices having an effective interaction length in excess of 6 cm, the value of $\chi_{eq}^{(3)}$ can be one order of magnitude larger than the $\chi^{(3)}$ available with the best transparent third-order nonlinear media. The experimental tests show that the produced phase-conjugated field is a very faithful replica of the input field, independently of signal bit-rate and modulation format. At the state of the art, the performance obtained with this kind of converters is unbeaten, as they allow obtaining at the same time high conversion efficiency and large conversion bandwidth. In fig. 3 we show a typical setup for OPC based on a PPLN waveguide, and the optical spectrum at the device output, showing the presence of the pump beam, the signal beam, and of the conjugated beam. We only mention here that the realization of a very efficient wavelength converter based on a PPLN waveguide, working at 100 Gb/s, was recently reported [14].

The main problem that is actually limiting the diffusion of these devices in real communication systems is the presence in the lithium niobate crystal of the photorefractive effect [15], which consists in a semi-permanent change of crystal refractive indices induced by a high-intensity light beam, having a photon-energy sufficient to excite electrons from a defect state to the conduction band. The second-harmonic light generated in the first step of the cascading process induces a change in the refractive indices, which is non-uniform in the waveguide cross-section. Such a change may cause a modification of the phase-matching condition when its impact is low, and a serious distortion of the beam propagation condition when the effect is more significant. A way to avoid this effect is to keep the device at high temperature (above 100 °C) during the operation. Another strategy is that of reducing the photorefractivity of the LN crystal by introducing, directly during the crystal growth, a small amount of appropriate dopant ions [16, 17]. At the state of the art the individuation of the best dopant is still open, but it seems reasonable to expect that a PPLN OPC device working at room temperature will be available in the near future.

4 OPC compensation method: theory and experiment

A typical optical-communication system for long-haul transmission is shown in fig. 4. The single-frequency CW output of a semiconductor laser working at a wavelength around 1550 nm (in the so-called “C-band” of optical

communications, corresponding to the wavelength range 1530-1560 nm) is amplitude-modulated by using the strong electro-optic effect of lithium niobate. By cascading two Mach-Zehnder lithium-niobate modulators, a 10 Gb/s stream of pulses with a full-width at half-maximum $T_{FWHM} = 45$ ps is produced. The information is transmitted under the form of a binary digital signal, using the so-called "On-Off Keying": the presence of an optical pulse in a time-slot means "bit 1", while the absence of the pulse means "bit 0". The signal is then boosted by using an erbium-doped fiber amplifier.

The transmission line is composed of a sequence of spans of a single-mode fiber, which can have a dispersion of ≈ -20 ps² km⁻¹ (in the optical-communication jargon, this is generally called "standard fiber", SMF, and is defined according to standard ITU-T G.652) or a lower β_2 , typically between -7 and $+7$ ps² km⁻¹ (generally called "non-zero dispersion-shifted fiber", NZDSF and defined by ITU-T standard G.655) which can exhibit positive or negative dispersion, according to fiber design. At the end of each span (between 40 and 100 km long) an EDFA is used to compensate for fiber losses.

The fiber dispersion can be compensated according to different schemes (called "dispersion maps") and the optimal "map" generally depends on system parameters. The description of dispersion mapping is outside the scope of this paper, we only mention here that two schemes can be used: lumped compensation (compensating elements are present only at the transmitter and/or receiver site) and distributed compensation (compensating elements are inserted after each fiber span). On the other hand, there is currently no technique applied to real systems for the compensation of distortions due to fiber nonlinear effects.

A very interesting aspect of the OPC is that, in principle, it allows compensating simultaneously both the dispersive and nonlinear effects occurring during propagation. If an OPC device is positioned in the middle of a system with a symmetrical distribution of both dispersive and nonlinear effects, the pulse evolution in the "second half" of the system is symmetric to that experienced in the first half, and thus all the distortions caused by both nonlinearity and even-order dispersion, can be compensated. This happens because the nonlinearity produced on a pulse is perfectly compensated by that produced on its "conjugated copy", an exact copy of the original pulse spectrally inverted and with an opposite value of accumulated dispersion. This approach is called Mid-Span Spectral-Inversion (MSSI). By combining the use of OPC with the description of the signal propagation through the so-called non-linear Schrödinger equation, the MSSI theory can be easily explained [18]. Unfortunately, in real systems, the presence of distributed fiber losses and of lumped amplification makes it almost impossible to produce a really symmetric distribution of fiber nonlinear effects, so that the exploitation of the MSSI approach has been considered for several years as a purely academic research topic.

Several proposals have been made in order to attain the nonlinearity compensation in non-symmetric systems, in most cases considering very specific and highly-customized transmission structures. Only recently the different approaches aimed at making OPC a viable solution for real systems have been included in a single reference frame [19].

The physical principle that allows compensating fiber nonlinear effects also in non-symmetric transmission systems is relatively simple: in long transmission spans (with a distance of 80 km or more between two subsequent amplifiers) the nonlinear effects are relevant only on a "highly-nonlinear" region of length L_{eff} (about 20 km-long) immediately after each amplifier, while the propagation between L_{eff} and the subsequent amplifier can be considered as purely dispersive. As a consequence it is possible to achieve an efficient nonlinearity compensation by imposing the symmetry requirements not on the all system structure, but simply on the corresponding "highly nonlinear" regions. Moreover, as the nonlinear effects produced in each region strongly depend on the pulse accumulated dispersion it is important to require that the optical pulses propagates in two corresponding nonlinear regions with the same amount of optical chirp. The basic idea underlying this method (called mid-nonlinearity temporal inversion, MNTI in the following), is better

explained by considering a graph, called PADD (Power vs. Accumulated Dispersion Diagram), that describes the evolution of the optical power as a function of the optical dispersion accumulated by the pulses in their propagation along the optical link. In order to achieve nonlinearity compensation the “high nonlinearity” regions appearing in the PADD must be symmetrically positioned with respect to the axis of zero accumulated dispersion [5].

Experiments testing the MSSI and MNTI methods for the simultaneous compensation of dispersive and nonlinear effects were performed on both amplitude-modulated [20] and phase-modulated transmission systems [21]. Here we shortly describe the experimental procedure and the main results, by principally referring to the simplest system, the amplitude-modulated one.

The signal to be transmitted consists of a $2^{31}-1$ pseudo-random bit sequence (chosen as “representative” of the possible transmission sequences), obtained by driving at the rate of 10 Gb/s an electro-optical modulator with a bit-error-rate tester. In the case of amplitude modulation the values 1 and 0 refer to the presence or absence of the pulse, whereas in the case of phase modulation the pulse is always present, but its phase can take the values 0 or π . At the receiver, the signal is amplified by a low-noise preamplifier, filtered to remove the amplified spontaneous emission introduced by the EDFA amplifiers outside the signal band, and then sent to a 95/5 splitter. The 5% output is brought to a clock-recovery-unit, required to sample the electrical signal exactly with the same frequency of the modulated signal, while 95% of the signal is sent via a variable attenuator to the photodetector. The standard test performed on digital communication systems is the comparison bit by bit between received and transmitted signal, yielding the so-called bit-error-rate (BER), which is defined as the fraction of bits which are not correctly “read” at the receiver. Typically a good system should show a BER value lower than 10^{-9} , meaning that less than 1 error in a billion of received bits is accepted. In the case of amplitude-modulated systems a simple qualitative test is represented by the observation of the so-called eye-diagram. The output of the photodetector is seen on the display of an oscilloscope, where the traces corresponding to different bits are all superposed. In the case of undistorted pulses only two levels are present at the output, so that one sees an “open eye”, whereas, in the presence of a strong distortion, all possible intermediate levels are present, so that a “closed eye” is observed. Although the eye-diagram does not give a precise quantitative information on the system performance, it is extremely useful to rapidly check the quality of the received signal.

The transmission line utilized in our experiments consists of six spans of a low- β_2 fiber (NZDSF), with a length of about 100 km each. The attenuation of the transmission fiber is 0.22 dB km^{-1} , and the dispersion parameter is $\beta_2 = 3.5 \text{ ps}^2/\text{km}$. To make more evident the nonlinear effects along this system, which is short compared to standard long-haul and ultra-long-haul links, the output power of the amplifiers (and input to fiber spans) was set to 16 mW, a value larger than the standard 10 mW one.

The standard configuration with in-line dispersion compensating fiber had a very low performance due to the distortion induced by the combined effect of nonlinearities and dispersion.

The OPC device used for the compensation test was a 7 cm long PPLN waveguide working on the cascade of two second-order processes. The pump and signal wavelengths were, respectively, 1552.52 nm and 1539.77 nm, matching the wavelengths defined by ITU standards for WDM transmission (channel 31 and 47, respectively). To realize the MSSI-based configuration all the in-line dispersion compensating fibers were removed, and the OPC device was simply placed at the middle position of the whole transmission line.

The realization of the MNTI scheme was more complex because, as described in ref. [5], in order to obtain the required symmetry in the PADD, dispersion-compensating components have to be added to the optical link. The experiment was performed by inserting two dispersion-compensating fibers, compensating the dispersion accumulated in about 40 km of propagation, one immediately before the OPC device and the other at the receiver.

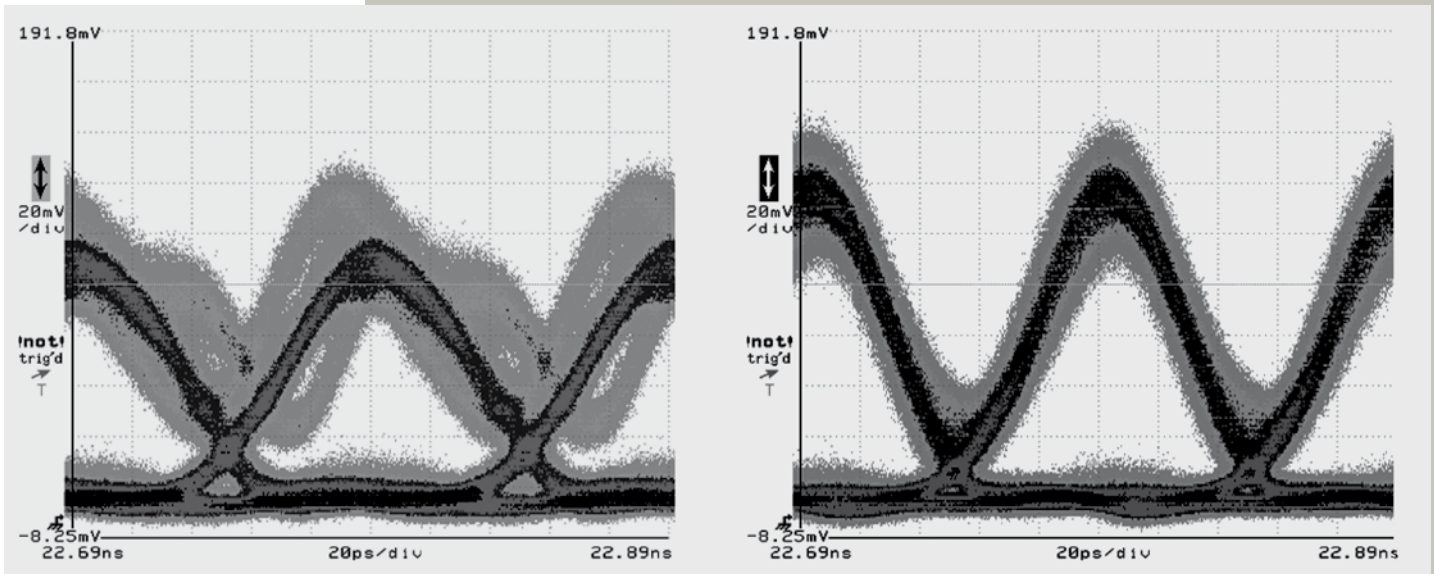


Fig. 5 The eye-diagram obtained using the MMSI approach (left) shows a significant distortion and amplitude fluctuations, as highlighted by the large grey areas. On the right, the signal obtained using MNTI is much cleaner and shows a significantly larger "aperture" of the eye, as the white region inside the diagram is significantly wider with respect to the MSSI case.

We show in [fig. 5](#) the two eye-diagrams obtained with, respectively, the MSSI and the MNTI scheme. By comparing the two eye-diagrams it is possible to observe that the signal obtained by MNTI is much cleaner than that achieved by simply following the MSSI approach, as in the latter case the nonlinear regions are not symmetrically positioned in the PADD, and hence there is no efficient compensation of fiber nonlinear effects. A more quantitative comparison is given by the BER curves presented in [fig. 6](#), where, following the standard approach, measurements are reported as functions of the average signal power seen at the input of the receiver. In a distortionless link the main source of errors is represented by the receiver noise, so the bit-error-rate is expected to decrease systematically as the signal power level grows. The BER curve obtained by inserting the OPC device between transmitter and receiver, without fiber propagation, shows that the OPC operation performed inside the PPLN waveguide does not introduce any signal distortion. The BER curves obtained after propagation along the 600 km link by using the two compensation methods described above present a decreasing behavior at low signal power and a saturating trend as the signal power is increased. The saturation indicates that the compensation methods leave some residual distortion, with MNTI working much better than MSSI.

A similar experiment was performed on a phase-modulated system by using exactly the same set-up of the amplitude-modulated system, except for the modulator, which was operating on a binary phase-modulation scheme. This was a more challenging test of the compensation method because such a system presents additional nonlinear noise, the Gordon-Mollenauer noise mentioned in [sect. 2](#), so that there was a widespread belief in the optical-communication community that it was not possible to realize an efficient compensation of such a noise in high-bit-rate phase-modulated systems. Some results are

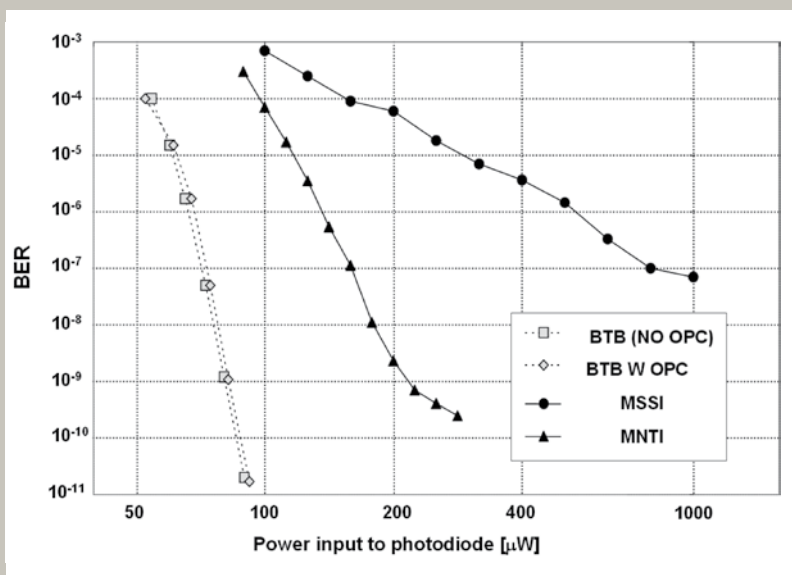


Fig. 6 BER curves as a function of the power input to the photodiode in the case of amplitude-modulated signal transmission in a 600 km long system. It is evident that, for a fixed amount of power input to the receiver the BER obtained using MNTI is significantly lower than that achievable by MSSI.

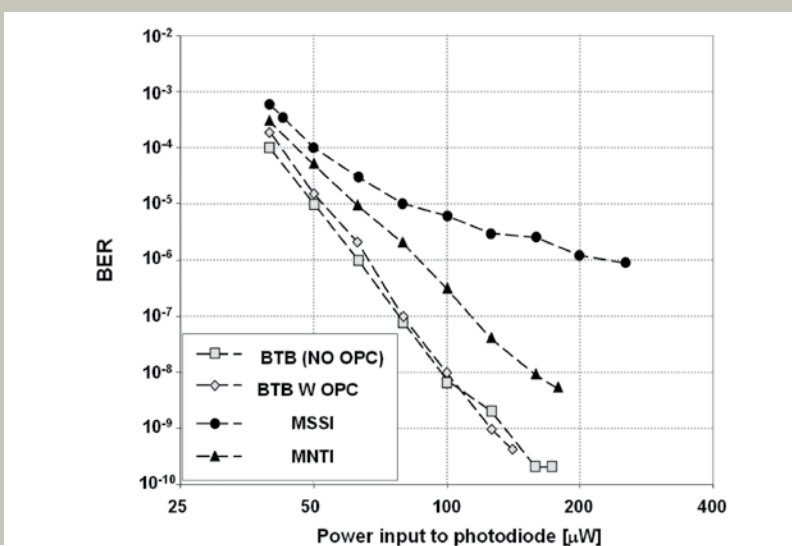


Fig. 7 BER curves as a function of the power input to the photodiode in the case of a phase-modulated transmission system. The behaviour is very similar to what observed in fig. 6 for amplitude-modulated signal transmission

shown in fig. 7. We see that the performance is very similar to the one obtained with the amplitude-modulated system. The reason is that the original treatment of nonlinear phase-noise [6] was made by considering optical links with relatively low bit-rate, in which the pulse shape modifications introduced by the fiber dispersion effect was negligible. On the contrary, if one considers real links, the interplay between nonlinearity and dispersion makes the pulse shape change very rapidly along the link, similarly to what happens in standard amplitude-modulated systems

5 Conclusions

In this article we have described how nonlinear optical devices can be usefully exploited for the compensation of signal distortions in long-distance high-bit-rate optical communications. The results obtained so far are promising, since they suggest that the optical-phase-conjugation method could provide compensation of signal distortions independently of the modulation format. The experiments, however, have been performed only on single-channel systems. It is still to be tested how the compensation method can be applied to WDM systems, in which many signals at different wavelengths travel simultaneously inside the optical link. Another aspect requiring further research is the optimum choice for the device performing OPC: the method based on the second-order optical nonlinearity can be adopted only if crystals having a negligible room-temperature photorefractivity are available, whereas the method based on the third-order nonlinearity has not yet shown a large enough conversion efficiency coupled with a sufficiently large conversion bandwidth.

Acronyms List

BER:	bit error rate	MSSI:	mid-span spectral inversion
BTB:	back-to-back	NZDSF:	non-zero dispersion-shifted fiber
DCF:	dispersion compensating fiber	OPC:	optical phase conjugation
EDFA:	erbium-doped fiber amplifier	PADD:	power vs. accumulated dispersion diagram
FWM:	four-wave mixing	PPLN:	periodically poled lithium niobate
GVD:	group velocity dispersion	SHG:	second-harmonic generation
ITU-T:	International Telecommunication Union - Telecommunication standardization sector	SMF:	standard single-mode fiber
LN:	lithium niobate	SOA:	semiconductor optical amplifiers
MNTI:	mid-nonlinearity temporal inversion	SPM:	self-phase modulation
		WDM:	wavelength division multiplexing

References

- [1] A general description of optical communications systems can be found in: G. P. Agrawal "Fiber-Optic Communication Systems" (J. Wiley & Sons, New York) 1997.
- [2] A. E. Willner, O. F. Yilmaz, J. Wang, X. Wu, A. Bogoni, L. Zhang, S. R. Nuccio, *IEEE Sel. Top. Quantum Electr.*, 17 (2011) 320.
- [3] R. A. Fisher, B. R. Suydam, D. Yevick, *Opt. Lett.*, 8 (1983) 611.
- [4] A. Yariv, D. Fekete, D. M. Pepper, *Opt. Lett.*, 4 (1978) 52.
- [5] P. Minzioni and A. Schiffrini, *Opt. Express*, 13 (2005).
- [6] J. P. Gordon and L. F. Mollenauer, *Opt. Lett.*, 15 (23) (1990) 1351.
- [7] R. W. Boyd, "Nonlinear Optics" (Academic Press, San Diego) 2003.
- [8] M. H. Chou, J. Hauden, M. A. Arbore, M. M. Fejer, *Opt. Lett.*, 23 (1998) 1004.
- [9] I. Cristiani and V. Degiorgio, *Riv. Nuovo Cimento*, 27, no. 12 (2004) 1.
- [10] A. Zapata-Beghelli and P. Bayvel, *J. Lightwave Technol.*, 26 (2008) 3403.
- [11] S. Diez, C. Schmidt, R. Ludwig, H.G. Weber, K. Obermann, S. Kindt, I. Koltchanov, K. Petermann, *IEEE J. Sel. Top. Quantum Electr.* 3 (1997) 1135.
- [12] A. Zhang and M.S. Demokhan, *Opt. Lett.*, 30 (2005) 2375.
- [13] H. Rong, Y. H. Kuo, A. Liu, M. Paniccia, O. Cohen, *Opt. Express*, 14 (2006) 1182.
- [14] P. Martelli, P. Boffi, M. Ferrario, L. Marazzi, P. Parolari, R. Siano, V. Pusino, P. Minzioni, I. Cristiani, C. Langrock, M. M. Fejer, M. Martinelli, V. Degiorgio, *Opt. Express*, 17 (2009) 17758.
- [15] T. R. Volk and M. Woehlecke, *Ferroelectr. Rev.*, 1 (1998) 195.
- [16] M. Asobe, O. Tadanaga, T. Yanagawa, H. Itoh, H. Suzuki, *Appl. Phys. Lett.*, 78 (2001) 3163.
- [17] G. Nava, P. Minzioni, W. Yan, J. Parravicini, D. Grando, E. Musso, I. Cristiani, N. Argiolas, M. Bazzan, M. V. Ciampolillo, A. Zaltron, C. Sada, V. Degiorgio, *Opt. Mater. Express*, 1 (2) (2011) 270.
- [18] E. Iannone, F. Matera, A. Mecozzi, M. Settembre, "Nonlinear Optical Communication Networks" (Wiley-Interscience, New York, NY) 1998.
- [19] P. Minzioni, *Fiber Integr. Opt.*, 28 (2009) 179.
- [20] P. Minzioni, I. Cristiani, V. Degiorgio, L. Marazzi, M. Martinelli, C. Langrock, and M. M. Fejer, *IEEE Photon. Technol. Lett.*, 18(9) (2006) 995.
- [21] P. Minzioni, V. Pusino, I. Cristiani, L. Marazzi, M. Martinelli, C. Langrock, M. M. Fejer, V. Degiorgio, *Opt. Express*, 18 (2010) 18119.

Vittorio Degiorgio

Vittorio Degiorgio has been a Full Professor of Physics of Matter at the University of Pavia, Italy, since 1980. He is the co-editor of four books and the author of more than 200 articles in the following fields: statistical properties of laser radiation, laser physics, laser light scattering and its applications to statistical physics, nonlinear optical materials and devices, wavelength conversion and its applications to optical-communication systems, fiber Raman lasers, and nonlinear pulse propagation in optical fibers and bulk media. He is "socio benemerito" of the Italian Physical Society and a Fellow of the Optical Society of America.

Paolo Minzioni

Paolo Minzioni accomplished his MSc in Electronic Engineering (2002) and his PhD degree (2006) at the University of Pavia. His PhD research activity, carried out in strong collaboration with both academic and industrial partners, has been dedicated to the design and use of integrated optical devices for next-generation optical networks. Since 2008 he is Assistant Professor at the University of Pavia. His current research activities encompass different fields, ranging from the study of new materials for nonlinear optical devices, to the design of biophotonic tools for single-cell trapping and manipulation, as well as to the study of optical-communication systems for very high-bit-rate transmission.

Ilaria Cristiani

Ilaria Cristiani took her PhD degree in Electronic Engineering and Computer Science at the University of Pavia in 1998. The PhD scientific activity was carried out at the Advanced Research Laboratories of Pirelli Cables & Systems in Milan. Since 1999 she is Assistant Professor at the Electronics Department of the University of Pavia. Her scientific activity is aimed at the experimental study of optical phenomena in guided-wave structures for the development of new devices for optical-communication systems and for biophotonics. She has co-authored more than 50 papers published in international journals.