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Nonlinear sculpturing of optical pulses with normally dispersive fiber-based devices

Christophe Finot[a,*], Ilya Gukov[b], Kamal Hammani[a], Sonia Boscolo[c]

[a] Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303 CNRS-Université de Bourgogne-Franche-Comté, 9 Avenue Alain Savary, BP 47870, 21078 Dijon Cedex, France

[b] Moscow Institute of Physics and Technology & Skolkovo Institute of Science and Technology, Moscow, Russia

[c] Aston Institute of Photonic Technologies, School of Engineering and Applied Science, Aston University, Birmingham B4 7ET, United Kingdom

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ABSTRACT

We present a general method to determine the parameters of nonlinear pulse shaping systems based on pulse propagation in a normally dispersive fiber that are required to achieve the generation of pulses with various specified temporal properties. The nonlinear shaping process is reduced to a numerical optimization problem over a three-dimensional space, where the intersections of different surfaces provide the means to quickly identify the sets of parameters of interest. We also show that the implementation of a machine-learning strategy can efficiently address the multi-parameter optimization problem being studied.

1. Introduction

In recent years, there has been a growing interest from the photonics community in the generation of non-conventional optical waveforms at repetition rates of several GHz because of their applications in all-optical signal processing and microwave signal manipulation. While sinusoidal, Gaussian and hyperbolic secant intensity profiles are now routinely produced by modulators or mode-locked lasers, other signal waveforms such as parabolic, triangular or flat-top pulse shapes remain rather hard to synthesize. Advances in fiber lasers have indicated promising ways to produce such waveforms [1–3], but the tunability of these lasers in terms of pulse repetition rate remains quite low and their experimental implementation and stability may require further work. Different approaches to the generation of specialized waveforms have also been explored. A first class of methods is based on photonic generation using special Mach-Zehnder modulator architectures [4,5], microwave photonic filters [6] or frequency-to-time conversion [7,8]. These methods can produce relatively (a few tens of picoseconds) long pulses. Another class of approaches aims at the synthesis of the target waveform directly in the frequency domain by adjustment of the amplitude and phase of different coherent spectral lines [9–11]. However, if the spectral lines involved are limited in number, the achievable duty cycle of the resulting pulse train will also be restricted. This limitation can be overcome by the use of ultra-short input pulses from a mode-locked laser. Pulse shaping using the Fourier-domain approach can indeed transform an ultra-short pulse into the desired shape, the transfer function in the frequency domain being the ratio of the target field distribution to the input field. In this context, picosecond and femtosecond pulse shaping has been achieved by use of spatial light modulators [12,13], super-structured fiber Bragg gratings [14], acousto-optics devices [15], and arrayed waveguide gratings [16]. Though being powerful and flexible, as the numerous successes of the fore-mentioned methods have demonstrated, the linear pulse shaping strategy has the intrinsic drawback that the bandwidth of the output spectrum is determined by the bandwidth of the input spectrum. Indeed, a linear manipulation cannot increase the pulse bandwidth, and so to create shorter pulses nonlinear effects must be used. In addition, a linear pulse shaper can only subtract power from the frequency components of the signal while manipulating its intensity, thereby potentially making the whole process power inefficient. The combination of third-order nonlinear processes and chromatic dispersion in optical fibers can provide efficient new solutions to overcome the drawbacks of linear pulse shapers [17]. In particular, it has been demonstrated that it is possible to take advantage of the progressive nonlinear reshaping of conventional laser pulses that occurs upon propagation in a normally dispersive fiber to generate various advanced temporal waveforms, including parabolic [18–21] and triangular [22–26] profiles.

However, the determination of the optimal parameters of a nonlinear fiber system to achieve desired pulse characteristics is more complex than that involved in linear spectral shaping, where only the input and target waveforms are required. Indeed, the nonlinear shaping depends on both the input pulse condition and the fiber properties. In

* Corresponding author.
E-mail address: christophe.finot@u-bourgogne.fr (C. Finot).

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previous works, we have proposed and validated some rules for the design of nonlinear pulse shaping fiber schemes [18,22,26], but without imposing any requirement on the output pulse characteristic parameters such as the pulse duration, for example. To the best of our knowledge, no general method for the design of fiber-based nonlinear pulse shaping has been developed to date, enabling the identification of the optimal working parameters for the generation of pulses with various prescribed characteristics. In this paper, we present such approach, which provides a comprehensive exploration of the possibilities offered by fiber-based nonlinear pulse shaping and the determination of the operational conditions within the space of system parameters for the formation of pulses with different, simultaneously optimized temporal features. After describing the degrees of freedom available in the system and the numerical procedure used for the characterization and optimization of the nonlinear shaping process, we illustrate our proposed approach through the examples of the generation of parabolic, triangular and rectangular waveforms with different pulse durations and time-bandwidth products. We also show that the multi-parameter optimization problem being considered can be efficiently addressed by using the machine-learning method of neural networks.

2. Principle and situation under investigation

In this section, we set up the problem to solve and outline the numerical procedure that we implement to deal with this problem.

2.1. Principle of nonlinear pulse shaping and available degrees of freedom

Nonlinear shaping in a normally dispersive fiber involves many degrees of freedom. A scheme for nonlinear shaping typically comprises two stages: a pre-chirping stage followed by a nonlinear propagation stage. Within such scheme, an initial pulse $\psi_0(t)$ with a peak power P_0 and a full-width at half maximum (fwhm) duration T_{in} is first propagated through a dispersive medium, such as a pair of diffraction gratings, a prism pair [27], a segment of hollow core or standard fiber with very low nonlinearity [23,24]. This linear propagation imprints a parabolic spectral phase onto the pulse, which is characterized by a chirp coefficient C_0 that can be positive or negative depending on the group-velocity dispersion (GVD) of the medium being normal or anomalous. The so obtained chirped pulse is then propagated through a normally dispersive fiber that reshapes both its temporal and spectral intensity profiles. According to the initial conditions of the input pulse, the initial stage of nonlinear dynamics in the fiber, where Kerr-induced self-phase modulation (SPM) dominates over GVD, may be very different. Indeed, input pulses with a negative chirp coefficient will experience spectral compression as a result of SPM [15,28–30], whereas for initially positively chirped (or Fourier transform-limited) pulses, spectral broadening will drive the nonlinear dynamics and eventually lead to optical wave-breaking [31]. Moreover, propagation in the nonlinear fiber is impacted by both GVD and SPM effects, which are characterized by the respective coefficients β_2 and γ. The length of the fiber L is also a crucial parameter that must be carefully selected. Therefore, from an experimental standpoint and for a given initial pulse waveform, at least six parameters can be adjusted to obtain the combination that is fit for purpose.

Note that in this paper we consider the simplest model of fiber propagation only including the dominant physical effects of the system. Indeed, higher-order linear effects such as third- or fourth-order dispersion, and nonlinear effects such as self-steepening or intra-pulse Raman scattering have negligible impact on pulses with picosecond-range durations as the ones being considered here. Note also that our discussion does not embrace the additional pulse shaping possibilities offered by advanced fiber designs such as fibers with distributed gain or longitudinally varying parameters [32–36]. Furthermore, we would like to emphasize that the focus of the present study is on pulse shaping in fibers with normal GVD. Anomalously dispersive fibers may sustain very different pulse dynamics, characterized by the emergence of solitonic structures that can be trickier to handle [37]. To summarize, even in the simplest configuration being studied, there are six physical parameters that must be used as input data for the nonlinear shaping problem, namely, (C_0, T_0, P_0, β_2, γ, L), where T_0 is a characteristic temporal value of the input pulse.

2.2. Features of the target pulses

The independent variation of the six system's parameters discussed above provides access to a large variety of output pulse temporal features. In addition to markedly different pulse shapes (i.e., parabolic, triangular and rectangular waveforms) whose generation has been studied in previous works [18,22,27], one can also achieve a very broad range of output pulse durations, bearing different levels of chirp. It is worth noting that contrary to what typically occurs upon nonlinear propagation in a fiber with anomalous GVD, using a normally dispersive fiber as the nonlinear shaping element favors the formation of pulses that are longer than the input pulses.

Different approaches are possible to characterize the pulse shape [18,22,38]. Here we compute the parameter of misfit M between the pulse temporal intensity profile I_N and the target shape fit I_T:

$$M^2 = \int (I_N - I_T)^2 dt \Big/ \int I_N^2\, dt. \tag{1}$$

We also consider the excess kurtosis (defined as $\mu_4/\sigma^4 - 3$, where μ_4 and σ are the fourth central moment and standard deviation of the pulse intensity profile, respectively, and 3 is the kurtosis of a Gaussian profile) as a measure of shape [38]. Shapes with a positive excess kurtosis have long and fat tails relative to a Gaussian shape, whereas negative excess kurtosis equals shorter and thinner tails than the Gaussian profile. We use the fwhm pulse duration T_{out} as a measure of the temporal extent of the pulse. The level of chirp present in the pulse is quantified by computing the Strehl ratio S, defined as the ratio of the maximum spectral brilliance of the actual pulse to the spectral brilliance obtained assuming a flat temporal phase of the pulse. Therefore, S is comprised between 0 and 1, with 1 defining a Fourier transform-limited waveform. The bandwidth at fwhm F_{out} of the frequency spectrum of the pulse is also used as a descriptor of the chirp.

2.3. Pulse propagation model

Pulse propagation in the fiber system follows the standard nonlinear Schrödinger equation (NLSE) [37]:

$$i\frac{\partial \psi}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 \psi}{\partial t^2} + \gamma\, |\psi|^2\, \psi = 0, \tag{2}$$

where $\psi(z,t)$ is the complex envelope of the pulse, z is the propagation coordinate and t is the retarded time. Note that the effects of linear loss can be neglected given the very low loss of silica fibers in the telecommunication wavelength window. As mentioned earlier, here we also neglect higher-order linear and nonlinear effects as the leading-order behavior is well approximated by Eq. (2).

The linear dispersive element can be described by Eq. (2) with $\gamma = 0$. As a result of GVD, the initial pulse acquires a parabolic phase in the spectral domain:

$$\widetilde{\psi} = \widetilde{\psi}_0 \exp\left(i\frac{C_0\omega^2}{2}\right), \tag{3}$$

where $\widetilde{\psi}$ denotes the Fourier transform of the pulse envelope, and the chirp coefficient C_0 equals the cumulative GVD. This spectral phase leads to temporal broadening of the pulse and the development of a chirp in the time domain, which is linear when C_0 is high (i.e., over far-field evolution). This stretched pulse then evolves in the nonlinear fiber according to Eq. (2).

It is useful to normalize Eq. (2) by introducing the dimensionless