Optical Fiber Technology 36 (2017) 125–129

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Linear sampling and magnification technique based on phase modulators and dispersive elements: The temporal lenticular lens

Javier Nuño *, Christophe Finot, Julien Fatome

Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303 CNRS-Université Bourgogne Franche-Comté, 9 av. A. Savary, 21078 Dijon Cedex, France

ARTICLE INFO

Article history:
Received 27 October 2016
Revised 13 February 2017
Accepted 10 March 2017
Available online 21 March 2017

Keywords:
All-optical signal processing
Fiber devices
Linear sampling
Phase modulation
Dispersion

ABSTRACT

In this work, we exploit the space/time duality in optics to implement a temporal lenticular lens allowing to simultaneously sample and magnify an arbitrary-shaped optical signal. More specifically, by applying a sinusoidal phase-modulation, the signal under test is propagated through a discrete dispersive element that samples and magnifies its initial waveform. Thanks to this temporal lenticular lens, optical sampling associated to an intensity magnification factor of 3.6 is experimentally demonstrated at a repetition rate of 10 GHz.

1. Introduction

In modern photonic systems, the sampling process has widespread applications in the fields of optical communications, metrology, clocking, sensing, spectral comb or arbitrary waveform generation. In this context, nonlinear effects have been demonstrated as potential key technologies to develop all-optical sampling devices [1–9]. Most of these methods are based on the nonlinear interaction among a train of ultrashort high-power pulses and the original signal, thus requiring an external mode locked picosecond pulse source. The basic physical phenomena involved in these interactions include four-wave mixing [5], cross-phase modulation (XPM) [6], nonlinear polarization rotation [8] or Raman soliton self-frequency shift [9].

More recently, an alternative nonlinear approach has been experimentally demonstrated at a sampling rate of 40 GHz, whilst providing a simultaneous 8-dB intensity magnification factor of the waveform [10]. Basically, during its co-propagation in a km-long fiber with a high-power sinusoidal pump beam, the waveform under test experiences a strong temporal phase modulation due to the XPM coupling. Subsequently, the signal undergoes a simultaneous temporal compression due to the normal dispersion regime of the fiber, leading to a periodic and localized nonlinear focusing effect [11]. In this new contribution, we propose a linear implementation of this process that does not require any external optical sampling beam. More precisely, here an electro-optic modulator is used to imprint the initial temporal phase modulation, while a programmable and compact spectral phase shaper enables an optimum sampling process through the formation of periodic pulses proportional to the initial waveform. Based on the analogy that can be drawn between usual spatial optics and ultrafast optics [12,13], such approach mimics in the temporal domain the behavior of a periodic lenticular lens that focuses different parts of an illuminating plane wave at equally spaced positions.

Our manuscript is organized as follows. In the second section, we describe the principle of our method and in particular, we highlight the analogy with the lenticular lens. Subsequently, we also present some design guidelines related to the intensity magnification factor and optimum dispersion. In Section 3, we then describe the experimental linear setup we implemented. The experimental results are presented in Section 4 and are compared with numerical simulations, demonstrating an excellent agreement. Finally, in Section 5, we summarize our work and trace out some conclusions and outlooks.

2. Principle of operation and design rules

Frequency chirp compensation of a parabolic time-dependent phase modulated signal passing through a dispersive medium imposing a quadratic spectral phase is a widely spread technique to produce ultrashort structures [14]. More generally, this focusing process can be viewed as the temporal analogue of an optical lens by using the space-time duality [15,16].

* Corresponding author.
E-mail address: j.nugno@gmail.com (J. Nuño).

http://dx.doi.org/10.1016/j.yofte.2017.03.006
1068-5200/

To imprint such an initial modulation within an incoming signal, taking advantage of the Kerr nonlinearity in optical fibers has been proved to be an attractive and efficient approach, for instance through self- or cross-phase modulation processes [17–19]. In a recent work, we have suggested and experimentally demonstrated an all-fibered sampling technique based on the XPM induced by a sinusoidal pump beam on the signal under test (SUT) combined to a simultaneous adiabatic compensation through normal chromatic dispersion [10]. In this configuration, the SUT experiences periodic local compression, leading to an efficient sampling of its intensity profile, not its phase, and intensity magnification of its waveform. Such passive magnification does not involve any gain of energy and should not be confused with the concept of temporal magnification in which an arbitrary waveform is slowed down without distorting its temporal shape.

An alternative approach to imprint such initial temporal phase modulation is to benefit from electro-optic devices [20]. Based on standard off-the-shelf telecom platform, this linear method has been proved more stable, less complex as well as more power efficient than nonlinear techniques. However, lower phase modulation amplitude can be achieved, so cascading several phase modulators is often required to achieve large frequency chirps [21]. Moreover, due to experimental constraints, synthetizing a perfect temporal quadratic phase modulation is quite difficult to achieve so most of the time, the initial modulation is replaced by a sinusoidal waveform that is close to a parabola at its extrema. In this case, when driven by RF sinusoidal signals, it is well known that the phase modulation of an initial continuous wave (CW) leads to the generation of high-repetition rate pulse trains after its propagation in a dispersive element [22,23]. By exploiting the space-time duality, as depicted in Fig. 1(a), such method of periodic temporal focusing presents some analogy with lenticular lenses in geometric optics where lenses are periodically reproduced and for which an incoming plane wave is focused at different equally spaced points.

In this novel contribution, we exploit a similar physical principle as the basis of our linear sampler. As depicted in Fig. 1(b), the modulation of the temporal phase produces a frequency chirp and in a second stage, a dispersive element that can be a linear optical fiber segment, a fiber Bragg grating [22], a pair of diffraction gratings [23] or a programmable spectral filter [24] imprints a quadratic spectral phase that temporally redistribute and concentrate the energy of the SUT in the central points. Consequently, the resulting signal is sampled at the frequency of the modulation and the peak power at these points is proportional to the initial waveform which is subsequently magnified in a noiseless process [25]. Note that in contrast to our preceding work published in Ref. [10] and for which the regime of chromatic dispersion had to be normal, here it can be chosen either anomalous or normal.

The design of our sampling device is rather simple as the final waveform is fully determined by only three parameters: the amplitude (θ) and frequency (f_m), associated with the temporal sinusoidal phase modulation and the accumulated dispersion (D) linked to the quadratic spectral phase of the second stage. Note that to be fully efficient, the period of the modulation has to be much shorter than the temporal width of the SUT. A strong frequency chirp of the SUT may also limit the performance of our technique by inducing variations of the magnification over the pulse duration. The sampled waveform $I_{out}(t)$ can be derived from the SUT $I_{in}(t)$ (which is here assumed for simplicity to be Fourier transformed) by the following formula:

$$I_{out}(t) \simeq \left| F^{-1}\left(F\left(\sqrt{I_{\text{in}}(t)}\exp(i\theta\cos(2\pi f_m t)\right) \quad \exp\left(-i\frac{1}{2}\frac{\lambda^2}{2\pi c}D(2\pi f)^2\right)\right)\right|^2 \tag{1}$$

with c being the speed of light, λ the central wavelength of the SUT, t and f being the temporal and frequency coordinates respectively. F and F^{-1} stand for the direct and inverse Fourier transform respectively. The magnifying factor G (defined as the power obtained at the sampling time, i.e. the peak-power of the resulting ultrashort pulse, divided by the power of the SUT at the same instant before sampling) can be inferred based on the following formula derived in the case of a quasi-continuous wave:

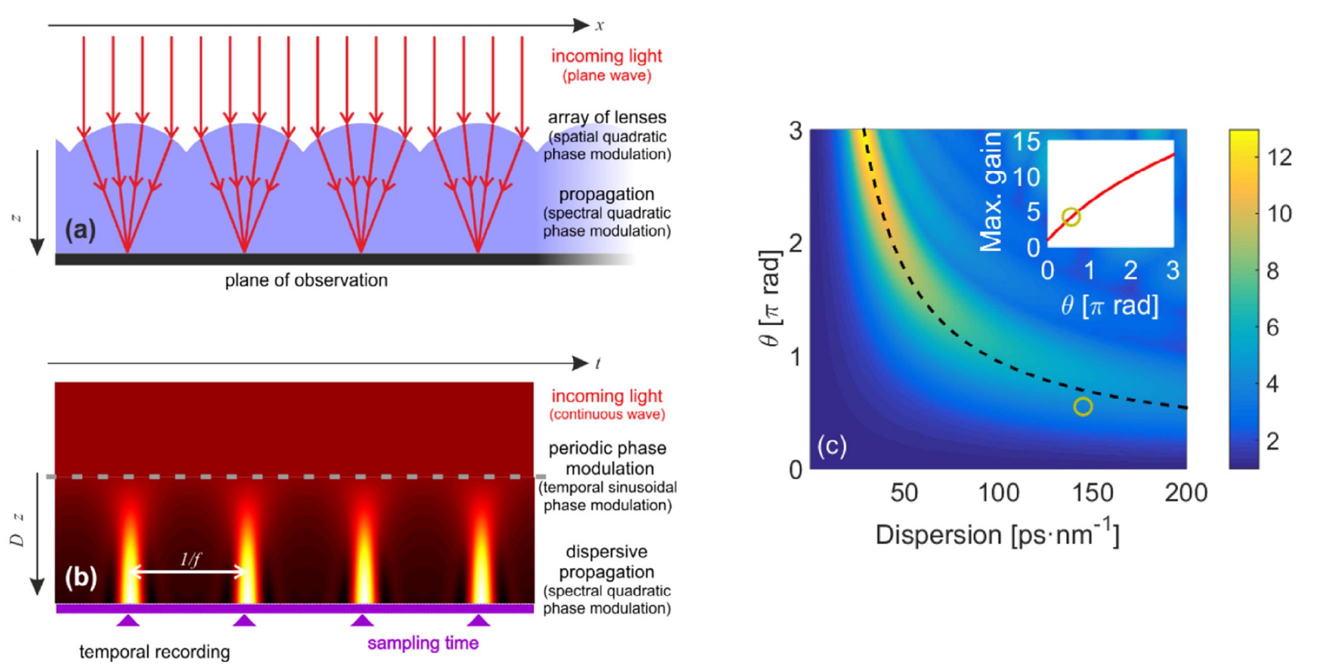

Fig. 1. (a) Lenticular lens illuminated by a plane wave. (b) Principle of the proposed temporal approach. (c) Magnifying factor as a function of both the amplitude θ of the phase modulation and the amount of chromatic dispersion. The dotted line represents the maximum magnifying factor according to the approximate prediction given by Eq. (3). In the inset, the maximum magnifying factor for each phase is plotted. The yellow circle represents the values in our experiments ($\theta = 0.55\pi$ and D $\approx$ 145 ps nm^{-1} in the fiber). In both cases, the frequency is equal to 10 GHz.