Temporal Reshaping of Picosecond Pulses at 1548 nm Based on Soliton Emission and Spatial Filtering in Nonuniform Ti : PPLN Waveguides

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***Abstract*—We studied numerically and experimentally an ultrafast passive nonlinear temporal reshaping mechanism based on spatial soliton emission in Ti periodically poled lithium niobate waveguides combined with spatial filtering. We demonstrated efficient temporal reshaping of 4-ps pulses at 1548 nm.**

***Index Terms*—All-optical device, devices, nonlinear optics, pulse propagation and solitons, ultrafast nonlinear optics.**

I. Introduction

IN optical telecommunications, multiple amplification and attenuation of information-carrying light pulses leads to an amplification of noise that quickly deteriorates the pulse shape and, therefore, increases the bit-error rate. To overcome such a signal distortion, an active technique of pulse regeneration can be used, which is usually performed by optoelectronic techniques. The so-called 3R regeneration implies a reamplification, reshaping, and retiming of the pulses. An all-optical method to perform these different regeneration functions would be potentially faster and with broader bandwidths. Several methods, based on third-order nonlinearities or nonlinear amplifiers have been proposed so far and are actively being studied to implement this function (see [1] and [2] and references therein). Second-order nonlinearities have not so far been studied to implement regeneration functions, in spite of the high nonlinear effects that they are likely to produce even at low input powers and in spite of their intrinsic ultrashort response time [3]. Temporal reshaping and saturable absorption using the combination of spatial soliton propagation with a spatial filtering slit have been recently proposed and demonstrated in quadratic media [4], [5]. In these studies, the quadratic soliton and the nontrapped noise propagate together in the same direction.

The efficiency of the temporal reshaping can be improved by spatially separating the soliton and the low-power noise. This can be achieved using walking solitons [6] where the fundamental and second-harmonic (SH) beams are trapped and undergo a direction different than the one followed by the signal at low power. No need of an engineered quasi-phase matched sample is required in that case, and the direction of the soliton is also controlled with simple parameters as the intensity, walkoff, and phase mismatch.

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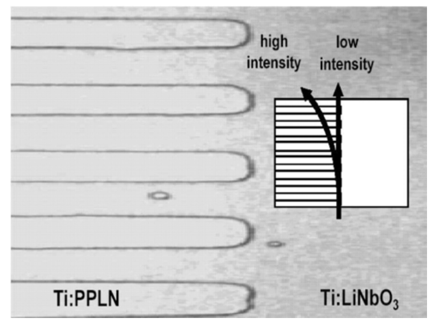

Fig. 1. Microscope picture of a section of the nonuniform waveguide surface with the boundary between the periodically poled and the homogenous lithium niobate region. Inset: geometry of the light beam-sample interaction.

Another solution consists in using nonlinear switching devices. It has been shown theoritically [7] and experimentally [8] that the soliton propagation could be controlled by engineering quasi-phase-matched structures. Soliton emission can be advantageously used for temporal reshaping since the soliton and the low-power noise also propagate with different directions.

In this letter, we studied a new ultrafast passive nonlinear temporal reshaping mechanism based on spatial soliton emission in nonuniform Ti periodically poled lithium niobate (PPLN) waveguides [9] combined with spatial filtering. We demonstrated efficient temporal reshaping of 4-ps pulses with noisy pedestal at 1548 nm. We refer to electromagnetic nonlinear type I interaction of a fundamental wave [(FF) at 1548 nm] and an SH wave (at 774 nm). We consider the propagation of signals across a quadratically nonlinear interface in titanium-indiffused PPLN slab waveguides, with FF only in input. The interface consists of the boundary between a periodically poled and a homogeneous lithium niobate region (see Fig. 1). In the whole device, the linear refractive index is homogeneous. At first, we consider an FF input pulse, in the PPLN region, close to the interface between the PPLN region and the unpoled region. At low intensity, the beam propagates along the interface, undergoes a spatial broadening because of diffraction inside the crystal. At high intensity and large enough phase-mismatch in the PPLN region, a quadratic spatial soliton is excited and spatially deflected (soliton emission [9]). The geometry of the light beam-sample interaction is reported in the inset of Fig. 1.

Then, we consider an FF main pulse (signal) with trailing and low-amplitude satellite pulses (noise). The satellite pulses are used as an example of distorted pulses and are launched into the waveguide. At low input intensity, signal, and noisy pulses propagate along the interface, in the same spatial direction. At high input intensity, we observed spatial soliton emission of the signal; signal and noisy pulses propagate along different spatial directions and at the output of the sample signal and noise are almost completely separated. A spatial filter placed at the output of the sample can be used to select the signal and suppress the noise. The efficiency of the reshaping mechanism depends on the input intensity, the aperture width and position.

II. Experimental Setup

The experiments were performed in a 58-mm-long $\mathrm{Ti:LiNbO_3}$ (Ti : LN) Z-cut planar waveguide. A microdomain structure of $\Lambda = 16.92\ \mu$m periodicity has been generated after waveguide fabrication by electric field assisted poling in one part of the waveguide only. The planar waveguide has a transition Ti : PPLN/Ti : LN (the nonlinear phase-mismatch interface) between periodically poled and unpoled regions. The sample was inserted in a temperature stabilized oven to allow operation at elevated temperatures ($T = 120$ °C–160 °C); in this way, photorefractive effects ("optical damage") could be minimized and temperature-tuning of the phase-matching conditions became possible. An all-fiber laser system was used as the source of 4-ps pulses (full-width at half-maximum (FWHM) in intensity) at 1548 nm (FF) of 1.7-nm spectral bandwidth and of a peak power of a few kilowatts at 20-MHz repetition rate. The setup of the laser system can be modified so that it delivers a main 4-ps pulse (signal) with trailing satellite pulses (noise). The thickness of the waveguide permitted the propagation of a single $\mathrm{TM_0}$ mode of 4-μm width at the FF; several TM modes are supported at the SH, but only the $\mathrm{TM_0}$ of 3-μm width is efficiently generated by the $\mathrm{TM_0}$ at the FF. The laser beam was shaped in a highly elliptical spot, nearly Gaussian in profile, with a spot of 4 μm (FWHM in intensity) along the guided dimension and with a spot of 60 μm along the perpendicular direction, and was polarized parallel to the Z axis of the PPLN to take advantage of the material's largest quadratic nonlinear coefficient $\chi^{(2)}_{zzz} = 2d_{33}$. The spatial beam profiles were recorded by imaging the output pattern on a vidicon camera. Temporal characterizations were monitored by a background free noncollinear autocorrelator. Two different filters were alternatively introduced, to select either the FF or the SH output.

III. Numerical Model

We model the electric fields E_1 and E_2, at ω_0 (FF) and $2\omega_0$ (SH), respectively, with $\omega_0 = 2\pi/\lambda_0$ and $\lambda_0 = 1548$-nm free space wavelength, propagating in the y direction, as $E_1(x,y,z,t) = 1/2[m_1(z)a_1(x,y,t)\exp(-j(\beta_{\omega_0}y + \omega_0 t)) + c.c.]$ and $E_2(x,y,z,t) = 1/2[m_2(z)a_2(x,y,t)\exp(-j(\beta_{2\omega_0}y + 2\omega_0 t)) + c.c.]$; $m_1(z)$ and $m_2(z)$ are the mode profiles in the guided dimension, $a_1(x,y,t)$ and $a_2(x,y,t)$ are the slowly varying envelopes, that obey the nonlinear coupled equations [10]

$$\begin{aligned}
&j\frac{\partial a_1}{\partial y} - j\beta'_{\omega_0}\frac{\partial a_1}{\partial t} - \frac{\beta''_{\omega_0}}{2}\frac{\partial^2 a_1}{\partial t^2} + \frac{1}{2\beta_{\omega_0}}\frac{\partial^2 a_1}{\partial x^2}\\
&\quad + \frac{\chi^{(2)}\omega_0}{2cn_{\omega_0}}\frac{\int m_2|m_1|^2dz}{\int |m_1|^2dz}a_2a_1^*e^{-j\Delta kz} = 0\\
&j\frac{\partial a_2}{\partial y} - j\beta'_{2\omega_0}\frac{\partial a_2}{\partial t} - \frac{\beta''_{2\omega_0}}{2}\frac{\partial^2 a_2}{\partial t^2} + \frac{1}{2\beta_{2\omega_0}}\frac{\partial^2 a_2}{\partial x^2}\\
&\quad + \frac{\chi^{(2)}\omega_0}{2cn_{2\omega_0}}\frac{\int m_2|m_1|^2dz}{\int |m_2|^2dz}a_1^2e^{j\Delta kz} = 0
\end{aligned} \tag{1}$$

where β represents the propagation constant, β' the inverse group velocity, β'' the inverse group-velocity dispersion; n is the refractive index, $\Delta k = 2\beta_{\omega_0} - \beta_{2\omega_0} + K_S$ is the effective mismatch, where $K_S = 2\pi/\Lambda$ and $\chi^{(2)} = 2/\pi\chi^{(2)}_{zzz}$ is the nonlinear coefficient. We assumed that the nonlinear interface is located at $x = 0$ in the (y,z) plane. To model the pulse propagation, two different numerical tools have been used. A standard finite difference vectorial mode solver was employed to determine the linear propagation properties in the slab waveguide, i.e., the mode profiles, the effective index, the propagation constant, the inverse group velocity, and the inverse group-velocity dispersion. In the case at hand, the crystal length corresponds to 3.7 times the FF diffraction length and to 5.6 times the walkoff length between FF and SH; the dispersive terms can be neglected. The phase-mismatch temperature dependency corresponds approximately to $1.66\pi/°$C. Finally, using a finite difference beam propagation technique, we solved the nonlinear coupled equations (1).

IV. Investigation

At first, experiments and numerical simulation were devoted to the characterization of spatial soliton emission. Investigations were carried out launching an FF input 4-ps pulse, in the PPLN region, close to the interface between the PPLN region and the unpoled region. At low intensity, the beam propagates along the interface, broadening because of diffraction inside the crystal. At high intensity, we succeeded in exciting a spatial soliton and we observed its spatial shift (soliton emission). Because of the temporal walkoff between FF and SH waves (20 ps), in comparison with the pulse duration (4 ps), the spatial trapping occured only for large positive phase mismatch ($\Delta kL \geq 9\pi$). Quadratic soliton excitation with pulsed light has been studied previously in details regarding the temporal shape of the pulse [11], [12]. The properties of the emission are intensity and phase-mismatch dependent (see [9] for details). In the limit of the available power, the larger output spatial shift is obtained at $\Delta kL = 9\pi$. Thus, the phase-mismatched interface affects high-amplitude waves, and does not affect low-amplitude waves.

Then, we modified the adjustments of the laser system so that it delivered a main 4-ps pulse (signal) with low-amplitude trailing satellite pulses (noise). The satellite pulses are used as

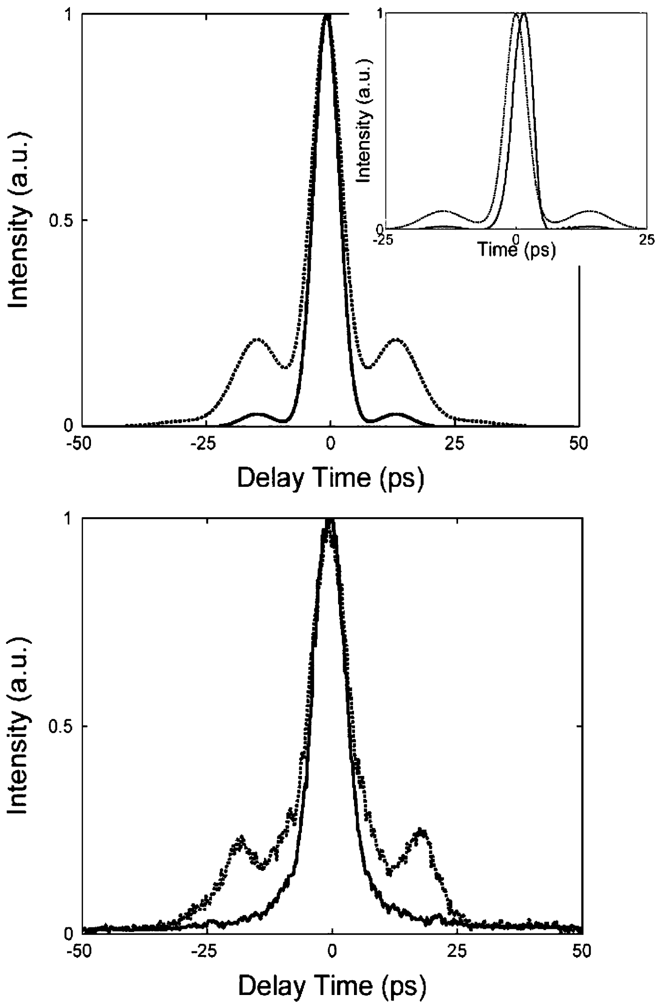

Fig. 2. (Top) Calculated and (bottom) measured FF autocorrelation traces at input (dotted line) and at output after temporal reshaping (solid line). The inset shows the FF calculated temporal profile at input (dotted line) and at output (solid line). The input intensity is $I = 200$ MW/cm^2 and the temperature of the sample is $T = 150°$C ($\Delta kL = 9\pi$).

an example of distorted pulses and are launched into the waveguide. At low input intensity, signal and noisy pulses propagate along the interface, in the same spatial direction; the profile of the autocorrelation at the output was close to the input one and exhibited large shoulders. At high input intensity, we observed spatial soliton emission of the signal; signal and noisy pulses propagate along different spatial directions and at the output of the sample signal and noise are almost completely separated. A spatial filter was placed at the output of the sample, where the soliton is emitted; with the aperture slit equal to the spatial soliton width, the pedestal in the autocorrelation trace disappeared. Typical experimental and numerical results are reported in Fig. 2.

The efficiency of the reshaping depends on the input intensity, and the phase-mismatch condition on the aperture width and position. The optimal temporal reshaping occured when the spatial output signal shift was maximum, the spatial filter was placed where the signal is emitted and the aperture slit was almost equal to the soliton width. The reshaping mechanism based on spatial soliton emission is more efficient than the reshaping mechanism proposed in [4], [5], because this new proposed mechanism achieve the almost complete spatial separation of signal and noise. This kind of processing is particularly interesting for high bit rate optical communication links where it could achieve all-optical reshaping of distorted pulses at very high speeds.

V. Conclusion

We demonstrated that spatial soliton emission in nonuniform Ti : PPLN planar waveguide combined with a spatial filter placed at the output face of the waveguide can operate as an ultrafast temporal reshaping device. We numerically and experimentally demonstrated that 4-ps distorted pulses at 1548 nm could be significantly cleaned up. It is worth noting that this nonlinear device is not restricted to a waveguide configuration and might be extended to bulk settings.

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