High-contrast linear optical pulse compression using a temporal hologram

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Abstract: Temporal holograms can be realized by temporal amplitude-only modulation devices and used for generation and processing of complex (amplitude and phase) time-domain signals. Based on the temporal hologram concept, we numerically and experimentally demonstrate a novel design for linear optical pulse compression using temporal modulation of continuous-wave light combined with dispersion. The newly introduced scheme overcomes the undesired background problem that is intrinsic to designs based on temporal zone plates, while also offering an energy efficiency of ~25%. This pulse compression scheme can ideally provide an arbitrarily high time-bandwidth product using a low peak-power modulation driving signal, though in practice it is limited by the achievable modulation bandwidth and dispersion amount.

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References and links

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1. Introduction

Linear pulse compression based on quadratic phase modulation (time lens) of continuous-
wave (CW) light followed by dispersion is an alternative approach to conventional mode-
locking for generation of ultra-short optical pulses [1–3]. A linear time lens can be practically
implemented by using an electro-optic phase modulator (EOPM) driven by a sinusoidal-like
RF signal [2, 4–12]. However, in conventional approaches based on time lens, there is a
tradeoff between the system temporal aperture (typically defining the maximum duration of
the signal to be processed) and frequency bandwidth (typically defining the system temporal
resolution). In particular, for conventional methods, their time-bandwidth product (TBP),
namely the product of temporal aperture and frequency bandwidth, is limited by the
achievable phase-modulation amplitude peak \( \Gamma_0 \) (TBP \( \sim \Gamma_0 / 2\pi \)) [6, 12]. Unfortunately, a high
phase-modulation amplitude, e.g. exceeding \( 10\pi \) [2, 13, 14], is difficult to achieve in a
practical EOPM device. To solve this problem, temporal zone plates, which are the temporal
countersparts of spatial zone plates, have been proposed as alternatives to time lenses [15–17].

Compared to time lenses, temporal zone plates do not exhibit the limiting tradeoff between
the temporal aperture and temporal resolution, enabling the realization of much higher TBPs
under similar experimental constraints. For example, an experimental TBP of 226, which is
much higher than that for a conventional linear time lens, has been realized by using temporal
zone plates [16]. Said other way, for the same level of TBP performance, the electronic drive
of an electro-optic temporal zone plate requires a much lower peak voltage (typically \( < V_\pi \),
where \( V_\pi \) is the half-wave switching voltage of the used electro-optic modulator) than that of
conventional linear electro-optic time lens designs. Temporal zone plates are particularly
interesting for optical pulse compression experiments because their increased temporal
aperture potentially enables crafting individual pulses with much higher energy levels. Notice
also that in this context, the minimum temporal width of the compressed pulse is determined
by the frequency bandwidth of the temporal zone plate. However, key limitations of temporal
zone plates include their relatively low light-collecting efficiency and significant undesired
background at their output.

Since its original proposal in 1948, spatial holography has been widely investigated for a
large variety of applications, such as data storage [18], three-dimensional microscopy [19],
and imaging [20]. Recently, a time-domain counterpart of spatial holography, referred to as
temporal holography, has been proposed [21]. Similar to the spatial case, temporal holography
can be realized by temporal amplitude-only (or intensity-only) modulation devices and used
for generation and processing of complex (amplitude and phase) time-domain signals. Thus,
this concept greatly simplifies present approaches aimed at similar generation and processing
tasks.

In this paper, we propose and investigate a novel linear optical pulse compression scheme
based on the temporal hologram concept. Similar to temporal zone plates, the linear pulse
compression scheme based on an electro-optic temporal hologram (temporal hologram
realized by electro-optic modulation) requires an electronic drive with a low peak voltage (~Vπ) and overcome the severe limitations on TBP of linear electro-optic time lenses. The TBP of the linear pulse compression scheme based on a temporal hologram can be ideally infinite, though in practice it will be limited by the available modulation bandwidth and dispersion amount. However, the temporal hologram system enables implementing only the desired quadratic phase-modulation (time-lens) function, avoiding the additional modulation terms that are intrinsic to temporal zone plates; in turn, this eliminates the detrimental undesired background that plague zone plates – based systems. This enables direct generation of output pulses with a significantly higher extinction ratio than their temporal zone plate counterparts. In addition, the energy efficiency of the proposed scheme is similar or superior to that of previous temporal zone plates.

This paper discusses fundamental and practical considerations of linear optical pulse compression based on a temporal hologram. Section 2.1 reviews the principle of temporal holograms, with a focus on designs based on temporal amplitude modulation. Section 2.2 presents the principle of the newly proposed linear optical pulse compression scheme based on a temporal hologram. In sections 3.1 and 3.2, numerical simulations and experiments for linear pulse compression with different output pulse-widths and different output frequency shifts are reported, respectively. Section 4 presents a comparative study between the performance of different linear pulse compression schemes based on temporal zone plates and temporal holograms, as compared with an ideal time-lens system. Finally, the main conclusions of this work are outlined in Section 5.

2. Principle of operations

2.1 Temporal hologram based on amplitude modulation

The Fourier transform adopted in this derivation is that the temporal and spectral amplitude of the optical signal are related by

\[
A(t) = \text{FT}^{-1} \left[ \tilde{A}(\omega) \right] = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{A}(\omega) \exp(j\omega t) d\omega,
\]

\[
\tilde{A}(\omega) = \text{FT} \left[ A(t) \right] = \int_{-\infty}^{\infty} A(t) \exp(-j\omega t) dt,
\]

where \(\text{FT}\) and \(\text{FT}^{-1}\) signify Fourier transformation and inverse Fourier transformation, respectively.

The scheme for implementing a temporal hologram is shown in Fig. 1. Briefly, as discussed previously [21], any desired complex (amplitude and phase) temporal modulation of CW light can be obtained through amplitude-only temporal modulation of the CW beam followed by an optical edge-pass filter (EPF, which enables all light at wavelengths shorter or longer than a prescribed wavelength to pass, essentially filtering out the remaining optical spectrum). Thus, the temporal hologram concept can be practically realized by using an electro-optic intensity modulator (EOIM), e. g., a conventional electro-optic Mach-Zehnder modulator (MZM), driven by a suitably designed modulating electronic waveform. The ideal temporal amplitude of the light after amplitude modulation is given by

\[
A_{\text{ideal}}(t) = A_{\phi}(t) \cos(\omega t + \phi(\omega t))
\]

\[
= \frac{1}{2} A_{\phi}(t) \exp[j\phi(\omega t)] \exp(j\omega t) + \frac{1}{2} A_{\phi}(t) \exp[-j\phi(\omega t)] \exp(-j\omega t)
\]

\[
= \frac{1}{2} E_{\phi}(t) \exp(j\omega t) + \frac{1}{2} E_{\phi}^*(t) \exp(-j\omega t),
\]
where $E_i(t) = A_\phi(t) \exp[j\phi(t)]$ is the complex optical information signal of interest and $E_i^*(t)$ is its conjugate. The spectrum of the modulated light can be obtained by Fourier transform, i.e.

$$\tilde{A}_{\text{mod}}(\omega) = \text{FT}[A_{\text{mod}}(t)] = \frac{1}{4\pi} \text{FT}[E_i(t)] \otimes \delta(\omega - \omega_i) + \frac{1}{4\pi} \text{FT}[E_i^*(t)] \otimes \delta(\omega + \omega_i).$$  \hspace{1cm} (4)

As shown in Eq. (4), the output consists of only two terms: the first term is the target modulation signal centered at frequency $\omega_i$ whereas the other is the conjugate of the target modulation centered at frequency $-\omega_i$. As discussed in [21], by properly biasing the electro-optic MZM, one can directly realize the amplitude modulation function in Eq. (3) (positive and negative amplitude variation), avoiding the detrimental effects associated with the presence of the DC term intrinsic to a temporal hologram based on pure intensity modulation (positive variations only). For instance, the energy efficiency of a temporal hologram based on amplitude modulation, defined as the portion of the input modulation intensity that is actually used to implement the target modulation function, is given by $(1/2)^2 \rightarrow 1/4 \, (~25\%)$, which is significantly higher than that of a temporal hologram based on intensity-only modulation [21].

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As shown in Fig. 1, the modulated light is sent through an EPF and as such, the target modulation signal is selected while the conjugated term is eliminated. Finally, the output temporal complex optical information of the system is given by

$$E_{\text{out}}(t) = \text{FT}^{-1}\left[\tilde{E}_{\text{out}}(\omega)\right] = \text{FT}^{-1}\left[\frac{1}{4\pi} \text{FT}[E_i(t)] \otimes \delta(\omega - \omega_i)\right]$$  \hspace{1cm} (5)

The most notable feature of a temporal hologram is that both intensity modulation and phase modulation can be realized by using a single intensity modulator, as proved by Eq. (5).
2.2 Linear pulse compression based on a temporal hologram

Linear pulse compression can be achieved by sending a linearly chirped optical pulse through a dispersive element [16]. The linearly chirped optical pulse is conventionally implemented by a time lens process, i.e., quadratic temporal phase modulation of CW light. In this work, we propose generating the desired chirped optical pulse through the use of a temporal hologram. Note that the phase chirp of the input pulse and the amount of subsequent dispersion must be exactly balanced to ensure optical pulse compression [1–3, 8, 16]. Assuming that the dispersion is \( \Phi_g \) (the slope of the group-delay curve as a function of radial optical frequency, \( \omega \)), then the target chirped optical pulse is given by

\[
E_{ch}(t) = A_{oo}(t) \exp\left(-j\frac{t^2}{2\Phi_g}\right).
\]

To generate such chirped optical pulse through a temporal hologram, the amplitude modulation function should be

\[
A_{\text{Mod}}(t) = A_{oo}(t) \cos\left(\omega t - \frac{t^2}{2\Phi_g}\right).
\]

The Fourier transform of this function is given by

\[
\hat{A}_{\text{Mod}}(\omega) = \text{FT}[A_{\text{Mod}}(t)] = \frac{1}{4\pi} \text{FT}[E_{ch}(t)] \otimes \delta(\omega - \omega_t) + \frac{1}{4\pi} \text{FT}[^*E_{ch}(t)] \otimes \delta(\omega + \omega_t).
\]

As shown by Eqs. (6)-(8), the temporal aperture, which is equal to the temporal duration of \( A_{oo}(t) \), i.e., \( \Delta T (-\Delta T/2 \leq t \leq \Delta T/2) \), can be ideally infinite, whereas in practice it is limited by the available modulation bandwidth. In particular, the target chirped pulse and its conjugate in Eq. (8) each have a quadratic temporal phase profile, inducing a total linear frequency excursion (bandwidth) of \( \Delta T/|\Phi_g| \). Thus, the frequency bandwidth of each of these terms increases for a longer temporal aperture, which in turn requires a higher frequency shift \( \omega_t \) and the associated, increased temporal modulation bandwidth. In particular, to avoid spectral overlapping of the two terms in Eq. (8), the following condition needs to be satisfied:

\[
\Delta T \leq 2|\Phi_g\omega_t|.
\]

As shown in Fig. 1, the electronic drive of the EOIM can be generated by an arbitrary waveform generator (AWG). According to the Nyquist-Shannon sampling theorem [22], the sampling rate \( f_s \) of the AWG should be at least twice broader than the bandwidth of the electronic waveform. To produce the electronic drive defined by Eq. (7), the sampling rate should satisfy the following inequalities:

\[
f_s \geq \frac{1}{\pi} \left( |\omega_t| + \frac{\Delta T}{2|\Phi_g|} \right) \geq \frac{\Delta T}{\pi|\Phi_g|}.
\]

Notice that the total frequency excursion produced by the quadratic phase in Eq. (6) along the aperture \( \Delta T \) is \( \Delta f = \Delta T/(2\pi|\Phi_g|) \). This total bandwidth excursion determines the temporal resolution of the time-lens system. For the case of a temporal imaging system with a rectangular temporal function, the temporal resolution (\( \delta t \)) is given by [6, 16]
\[ \delta t = \frac{1}{\Delta f} = \frac{2\pi|\Phi_0|}{\Delta T} \geq \frac{2}{f_s}. \] (11)

Hence, the TBP of the temporal hologram is ultimately limited to

\[ \text{TBP} = \frac{\Delta T}{\delta t} = \frac{\Delta T^2}{2\pi|\Phi_0|f_s}. \] (12)

As shown by Eqs. (9), (10) and (12), the temporal aperture and TBP of the temporal hologram in the proposed linear pulse compression scheme are linearly proportional to the sampling rate of the AWG and the dispersion amount, following a similar set of equations to those of temporal zone plates [16, 17]. Thus, similar to temporal zone plates, the TBP of the temporal hologram can be ideally infinite by lowering down the time-lens frequency chirp, whereas it is limited by the achievable dispersion and AWG sampling rate in a practical scheme [16, 17].

Recall that the target chirped optical pulse can be directly recovered from the amplitude-modulated optical signal using an EPF to filter in the corresponding spectral term in Eq. (8), which is given by

\[ E_{fil}(t) = \text{FT}^{-1} \left\{ \frac{1}{4\pi} \text{FT} \left[ E_{ch}(t) \right] \otimes \delta(\omega - \omega_0) \right\} = \frac{1}{2} E_{ch}(t) \exp(j\omega t). \] (13)

By sending the obtained chirped optical pulse through dispersion, we obtain the following temporal wave amplitude at the system output:

\[ A_{out}(\tau) = E_{fil}(t) \otimes h_{time} \exp \left( \frac{jt^2}{2\Phi_0} \right) = \frac{1}{2} h_{time} \exp \left[ j\left( \tau + \Phi_0 \omega_0 \right) \right] A_{\omega_0} \left( \frac{\tau}{\Phi_0} \right), \] (14)

where \( h_{time} \) is a constant that depends on \( \Phi_0 \), and \( \tau = t - \Phi_0 \omega_0 \) is normalized time. Note that for pulse compression, the input signal envelope \( A_{\omega_0}(t) \) is supposed to have a long time duration. Therefore, the intensity profile of the system output is a narrow pulse. The temporal duration of the output optical pulse depends on the dispersion and temporal duration of the input signal envelope.

3. Numerical simulations and experimental results

In this Section, we present numerical simulations and experimental results for linear optical pulse compression based on the proposed temporal amplitude hologram concept.

3.1 Linear pulse compression with different output pulsewidths

An illustration of the conducted experiment is shown in Fig. 1. Light from a CW laser at a wavelength of 1,549.8 nm is amplified and sent through a 40-GHz EOIM (\( V_x = 4.6 \text{V} \)), which is driven by the electronic waveforms generated by a 24 Gsamples/s AWG and amplified by a 12.5-GHz electronic amplifier. The electronic bias for the EOIM is \( 1.5 V_x \). As predicted by Eq. (8), there are two frequency components, corresponding to the target phase-modulated signal and its conjugate, respectively. The modulated light is then amplified and filtered by an EPF to obtain the target phase-modulated waveform. In particular, the EPF used in all our
experiments enables all light at wavelengths shorter than 1549.78 nm to pass, essentially filtering out the remaining optical spectrum. The filtered light is sent through a reflective linearly chirped fiber Bragg grating (LCFBG, working from 1548.91 nm to 1552.52 nm), which introduces a predominantly 1st-order dispersion of $-10,000$ ps/nm. After dispersion, the light is measured with a 45-GHz photo-detector coupled to an electronic sampling oscilloscope.

We characterized our system for the case of four different temporal apertures, as defined by the duration of the input Gaussian-like modulation envelope, with intensity FWHMs of 100 ps, 200 ps, 300 ps, and 400 ps, respectively. The ideal electronic temporal modulation waveforms (thick orange lines), which are calculated using Eq. (7), are shown in Fig. 2. The implemented frequency shift between the target and conjugated signal, i.e. $\omega_i/2\pi$, is 6 GHz. The slight distortions between the measured electronic modulation waveforms (thin black lines, directly measured with the same sampling oscilloscope) and ideal electronic waveforms are mainly due to the limited bandwidth of the AWG. Figure 3 shows good agreement between the corresponding numerically calculated (thick orange lines) and measured (thin black lines) optical intensity waveforms after modulation.

Figure 4 shows the corresponding numerically calculated (thick orange lines) and measured (thin black lines) spectra of the modulated optical waveforms. As predicted by Eq. (8), there are two well-separated frequency bands, which correspond to the target linearly chirped signal and the conjugated term, respectively. By using an EPF, the target linearly chirped signal is selected, as shown in Fig. 5. Finally, the target linearly chirped signal is sent through the dispersive LCFBG. The compressed output pulses are shown in Fig. 6. There is also a fairly good agreement between the numerical simulation (thick orange lines) and experimental results (thin black lines). In particular, the intensity FWHM of the calculated output pulses in Figs. 6(a)-6(d) are respectively 361.8 ps, 177.1 ps, 116.8 ps, and 92.8 ps, whereas the intensity FWHM of the measured output pulses in Figs. 6(a)-6(d) are respectively 430.7 ps, 194.3 ps, 136.3 ps, and 122.6 ps. There are two possible reasons for the slight deviations between calculations and measurements. The first one is due to deviations between the measured electronic modulation waveforms and the ideal electronic waveforms, in turn induced by limitations in the AWG bandwidth, as shown in Fig. 2. The second one is as a result of the imperfect EPF, which deviates from the ideal rectangular-like spectral edge-pass transmission response. As a result, the spectrum of the signal after filtering in Fig. 5 is slightly different from the left half of the corresponding spectrum in Fig. 4. Thus, the measured output temporal waveforms have slightly larger time widths than those expected from the theoretical calculations.

![Fig. 2](image1.png)  
**Fig. 2.** Numerically calculated (thick orange lines) and measured (thin black lines) electronic waveforms for temporal amplitude modulation in the implemented temporal holograms. (a)-(d) correspond to four temporal holograms with different (increasing) temporal apertures.

![Fig. 3](image2.png)  
**Fig. 3.** Numerically calculated (thick orange lines) and measured (thin black lines) optical intensity waveforms after temporal amplitude modulation. (a)-(d) correspond to the four temporal holograms with different temporal apertures shown in Figs. 2(a)-2(d).
3.2 Linear pulse compression with different frequency shifts

In this Section, we report characterization of our proposed scheme for 3 different frequency shifts between the target and conjugated signals, i.e. $\omega_i/2\pi$, which are 6 GHz, 9 GHz, and 12 GHz, respectively. The frequency shift can be directly set by modifying the electrical signal generated by the AWG, as long as the sampling rate of the AWG is sufficiently high, as per the relationship in Eq. (10). Temporal apertures for these three experiments are all 200 ps.

The ideal electronic modulation waveforms (thick orange lines), which are calculated through Eq. (7), are shown in Fig. 7. Figure 8 presents the corresponding numerically calculated (thick orange lines) and measured (thin black lines) optical intensity profiles for the modulated waveforms. As shown in Fig. 7 and Fig. 8, there is a good agreement between the calculated and measured modulation waveforms.

Figure 9 shows the numerically calculated (thick orange lines) and measured (thin black lines) spectra of the optical modulated waveforms. As designed, the frequency shifts for the three evaluated cases are 6 GHz, 9 GHz, and 12 GHz, respectively. The modulated light is then filtered by an EPF so that the target signal is selected, as shown in Fig. 10. After that, the filtered light is sent through the LCFBG. The compressed output pulses are shown in Fig. 11. Because the input modulation envelopes used in the 3 cases are the same, the FWHM of the output pulses are similar. Nonetheless, the presented results confirm that the experimental output pulses slightly deviate from the theoretical predictions; we attribute these deviations to the same issues discussed in Section 3.1, i.e., the limited bandwidth of the AWG and the imperfect spectral response of the EPF.
Fig. 7. Numerically calculated (thick orange lines) and measured (thin black lines) electronic waveforms for temporal amplitude modulation in the implemented temporal holograms. (a)-(c) correspond to three temporal holograms with different (increasing) frequency shifts.

Fig. 8. Numerically calculated (thick orange lines) and measured (thin black lines) optical intensity waveforms after temporal amplitude modulation. (a)-(c) correspond to the three temporal holograms with different frequency shifts shown in Figs. 7(a)-7(c).

Fig. 9. Numerically calculated (thick orange lines) and measured (thin black lines) spectra of the optical modulated waveforms. (a)-(c) correspond to the three temporal holograms with different frequency shifts shown in Figs. 7(a)-7(c).

Fig. 10. Numerically calculated (thick orange lines) and measured (thin black lines) spectra of the optical spectra after edge-pass filtering. (a)-(c) correspond to the three temporal holograms with different frequency shifts shown in Figs. 7(a)-7(c).
4. Comparison of different linear pulse compression schemes

As discussed in the introduction, linear pulse compression schemes based on time lenses, temporal zone plates and temporal holograms have their limitations or advantages. In this Section, we evaluate and compare the performance of these linear pulse compression schemes through numerical simulations.

The basic experimental setup for linear pulse compression based on temporal zone plates is the same as in Fig. 1 [16]. Note that there are two types of temporal zone plates, referred to as temporal intensity zone plates (TIZPs) and temporal amplitude zone plates (TAZPs), respectively based on temporal intensity modulation and temporal amplitude modulation [17]. Compared to TIZPs, TAZPs have a higher energy efficiency and a lower output background [17]. The linear pulse compression scheme based on time lenses is also the same as in Fig. 1, except that the EOIM is replaced by an EOPM.

The electronic modulation waveforms for the implemented TIZP, TAZP, temporal hologram and time lens are shown in Figs. 12(a)-12(d), respectively. Note that these devices are designed with the same chirp factor and the same temporal aperture, so that we can clearly compare the performance of these systems by observing the output compressed temporal pulses. The electronic waveforms in Figs. 12(a)-12(c) are sinusoidal and thus, in contrast to a time-lens scheme, these corresponding systems do not require a high peak voltage (usually less than \(V_\pi\)). We recall that the requirement for a high peak voltage is the most critical limitation for a time-lens-based system. In particular, the needed peak voltage for a time-lens-based system is approximately given by the product of 2\(V_\pi\) and the target TBP [6], so in the example reported here, the simulated time-lens process would require a peak voltage exceeding 20\(V_\pi\), itself a very challenging requirement for most practical devices. Another important issue coming out from our comparative analysis is that the modulation bandwidth that is required to implement the temporal hologram is higher than that for the TIZP or the TAZP, as directly seen from Figs. 12(a)-12(c). Said other way, for a given limited modulation bandwidth, the design temporal aperture for a system based on a temporal hologram is smaller than that based on a TIZP or a TAZP. Figure 13 presents the numerically calculated optical intensity profiles for the corresponding modulated waveforms.

Fig. 12. Numerically calculated electronic waveforms for temporal amplitude modulation (a-c) and for temporal phase modulation (d). (a)-(d) correspond to the implemented TIZP (a), TAZP (b), temporal hologram (c) and time lens (d), respectively.
At the system output, the temporal intensity profiles of these systems are shown in Figs. 14(a)-14(d). To help visualizing the output signal background, Figs. 14(e)-14(g), respectively corresponding to Figs. 14(a)-14(d), show the intensity profiles in log scale. As a first important observation, the output background in Fig. 14(a) [Fig. 14(e)] is the largest; the output background in Fig. 14(b) [Fig. 14(f)] is significantly reduced, though showing an undesired, significant floor background over the entire system temporal aperture; this background is notably lower in Fig. 14(c) [Fig. 14(g)], where it shows a rapid decreasing outside the pulse duration, similarly to the compressed output pulse from the ideal time-lens system, shown in Fig. 14(d) [Fig. 14(h)]. In quantitative terms, the extinction ratios of the main lobes for these systems are 6.73 dB, 12.61 dB, 13.59 dB, and 13.53 dB, as shown in Figs. 14(e)-14(h). These results confirm that the performance of temporal holograms is superior to that of temporal zone plates in terms of reduced output background, leading to an increased output extinction ratio. As the same chirp factor is assumed for all simulated cases, the FWHM of the temporal outputs corresponding to the different evaluated systems are nearly identical. Additionally, the energy efficiencies for these systems can be estimated as 13.23% (2.97/22.45), 30.82% (6.92/22.45), 25.26% (5.67/22.45) and 100% (22.45/22.45), which are close to the corresponding theoretical values, i.e., 6.25% [16], 25% [17], 25% and 100%, respectively. For the first and second cases, the deviation is due to the output background and in particular, the deviation increases with the output background.

Figures 15(a)-15(d) show the output spectra corresponding to the compressed pulses for the four evaluated schemes. The spectrum of the ideal output in a time-lens-based system is shown in Fig. 15(d), and any deviation from this ideal spectrum translates into the presence of undesired background in the compressed temporal pulse. As expected, the output spectrum of the system based on a temporal hologram, shown in Fig. 15(c), is the same as the ideal one in Fig. 15(d); the output spectrum of the system based on a TAZP [Fig. 15(b)] differs from the
ideal one in Fig. 15(d), but it has the same spectral envelope; the output spectrum of the system based on a TIZP [Fig. 15(a)] is similar to that of the TAZP spectrum, Fig. 15(b), as confirmed by the zoom presented as an inset in Fig. 15(a), but it exhibits a very pronounced additional center lobe, which is the main reason for the severe output background.

In summary, the performance of four different linear pulse compression schemes – based on TIZPs, TAZPs, temporal holograms and time lenses – have been compared. As shown in Table 1, the proposed scheme based on temporal holograms needs a relatively low peak voltage, while overcoming the TBP limitation of linear electro-optic time lenses. In addition, the proposed temporal-hologram scheme has an implementation complexity that is very similar to that of a temporal zone plate, whereas it is capable of generating pulses with a much lower undesired output background, a higher output extinction ratio, and a superior or similar energy efficiency to that of temporal zone plate designs.

Table 1. The performance of various linear pulse compression schemes.

|                  | TIZPs | TAZPs | Temporal holograms | Time lenses |
|------------------|-------|-------|--------------------|-------------|
| Realization      | EOIM  | EOIM  | EOIM               | EOPM        |
| Needed peak voltage | Low (≤V<sub>π</sub>) | Low (≤V<sub>π</sub>) | Low (≤V<sub>π</sub>) | High (≈2V<sub>π</sub> × TBP) |
| Undesired output background | High | Medium | Low                | Low         |
| Extinction ratio | Low (6.73 dB) | Medium (12.61 dB) | High (13.59 dB) | High (13.53 dB) |
| Energy efficiency | Low (6.25%) | Medium (25%) | Medium (25%) | High (100%) |
| TBP              | (2πf<sup>+</sup> | (2πf<sup>-</sup> | (πf<sup>-</sup> | Low (Peak voltage / 2π) |
|                  | Φ<sub>1</sub>) | Φ<sub>1</sub>) | Φ<sub>1</sub>) | 2π) |

5. Discussions and conclusions

In summary, a novel temporal hologram concept based on temporal amplitude modulation has been introduced and demonstrated for implementing a time-lens process. The concept has been validated through linear optical pulse compression experiments. The proposed temporal amplitude hologram concept allows one to overcome the severe limitations on TBP (ratio between temporal aperture and resolution) of linear electro-optic time lenses. In particular, the temporal amplitude hologram can be ideally designed to offer a temporal aperture as large as desired, practically limited only by the amount of dispersion needed in the processing systems. In addition, the required peak voltage of the electronic drive (~V<sub>π</sub>) is much lower than that typically required for linear electro-optic time lenses. Compared to temporal zone plates, the use of a temporal amplitude hologram overcomes the undesired background problem that is intrinsic to these previous schemes while providing similar or superior energy efficiency (25%). The latest is achieved through an edge-pass filtering process that enables keeping only the time-lens (quadratic phase-modulation) term of interest. This procedure is simply not possible in conventional temporal zone plates where all phase modulation terms are centered on the same optical wavelength.
The newly proposed time-lens approach is particularly interesting for linear pulse compression experiments as it directly enables a much higher TBP than in the case of a conventional linear time-lens process by using an electronic drive with a much lower peak voltage (∼Vπ). The significant improvements of higher extinction ratio and lower output background offered by the temporal hologram solution over temporal zone plates represent an additional important advantage in the context of pulse compression applications. A drawback of the hologram approach is that the frequency bandwidth of the equivalent time lens is ultimately limited by the available modulation bandwidth, typically requiring at least twice the modulation bandwidth of an equivalent temporal zone plate. However, higher resolutions could be achieved without compromising the input temporal aperture or increased per-pulse energy by simply combining the temporal hologram concept with a conventional time-lens process, e.g., by compressing further the output pulse from the temporal hologram scheme using a conventional time-lens-based system. Also, in this paper, linear pulse compression at a wavelength of ∼1550 nm has been shown. However, it is worth mentioning that electro-optic modulators and dispersive devices are available across a broad range of wavelength regimes, not limited to the telecommunication window demonstrated here. Thus, the proposed method also represents a promising alternative for linear short pulse generation and compression at exotic wavelengths, where pulse generation may be challenging by more conventional methods, e.g. pulsed laser techniques.

More generally, the high TBP, high contrast, high energy efficiency and low output background features offered by the temporal amplitude hologram concept may prove useful for many other systems based on the use of time lenses and temporal zone plates.