# Novel temporal zone plate design with improved energy efficiency and noise performance

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**Abstract:** We propose and experimentally demonstrate a new kind of temporal zone plates, i.e., temporal amplitude zone plates, providing a 96% improvement in energy efficiency and significantly reducing noise background as compared with previous temporal intensity zone plates.

By suitably combining dispersion and a time lens, applications such as temporal imaging [1], linear pulse compression [2] and time-to-frequency mapping [3] of optical waveforms have been realized. A time lens is conventionally implemented by imparting a quadratic phase shift, or linear frequency chirp, across a signal in the temporal domain. A main figure of merit of a time lens is given by its time-bandwidth product (TBP), which is the product of the temporal aperture (typically defining the maximum duration of the signal under analysis) and the frequency bandwidth (typically defining the temporal resolution). However, in conventional time lenses, there is a severe tradeoff between the temporal aperture and temporal resolution. To solve this problem, temporal zone plates, which are the temporal counterparts of spatial zone plates, have been proposed as alternatives to time lenses [4]. 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 [4]. However, temporal zone plates are ultimately limited by their low light-collecting efficiency and the noise background of their output. In previous works, two kinds of temporal zone plates have been proposed [4]. They are based on intensity and phase modulation, respectively referred to as "temporal intensity zone plates (TIZPs)" and "temporal phase zone plates (TPZPs)". In particular, although TIZPs provide a lower energy efficiency than TPZPs, TIZPs offer a significantly improved performance in terms of noise background. Therefore, in this paper, we propose and demonstrate a novel kind of temporal zone plates, referred to as temporal amplitude zone plates (TAZPs), capable of significantly improving the performance of TIZPs, in terms of both light-collecting efficiency and noise background, without requiring any modification on the basic experimental setup.

Previously, TIZPs have been implemented by temporal intensity modulation, with a positive-only amplitude-transmittance function defined as follows:

$$A_G(t) = 1/2 + (1/2)\cos(at^2) = 1/2 + (1/4)\exp(jat^2) + (1/4)\exp(-jat^2), \quad (1)$$

for $-\Delta t/2 < t < \Delta t/2$, in which $\Delta t$ is the temporal aperture, and $a/\pi$ is the modulation frequency chirp, which is related with the time-lens frequency chirp. Because temporal quadratic phase variations can be interpreted as being equivalent to time lenses, Eq. (1) confirms that the defined amplitude-transmittance function is equivalent to the sum of a positive and a negative time lens, with different focal times, plus a bias term. Therefore, the maximum light-collecting efficiency of such a system, defined as the portion of light that is focused by the desired time-lens term, is given by the square of the corresponding coefficient, i.e. $(1/4)^2 \rightarrow 1/16$. To improve the performance of light-collecting efficiency and noise background, we propose a novel TAZP, which is realized by positive and negative amplitude modulation. The amplitude-transmittance function of the TAZP is defined as

$$A_G(t) = \cos(at^2) = (1/2)\exp(jat^2) + (1/2)\exp(-jat^2). \quad (2)$$

Compared to Eq. (1), the bias in Eq. (2) is eliminated and thus the associated portion of noise is intrinsically lower than that of a TIZP. Moreover, the maximum light-collecting efficiency of the TAZP is estimated as $(1/2)^2 \rightarrow 1/4$, which is four times higher than that of a TIZP. Notice that to realize the needed modulation for a TAZP, the peak-to-peak amplitude of the modulating drive must be 2 times higher than that of a TIZP, as shown in Eq. (2), Fig. 1 and Figs. 2(a)-(b). A TIZP and the proposed TAZP can be both practically realized by using an electro-optic intensity modulator (EOIM), e.g., a conventional electro-optic Mach-Zehnder modulator driven by the same bisa point (note that the driving electronic waveforms are different). Interestingly, the novel TAZP concept could be also explored to improve spatial zone plates.

To compare the performance of a TAZP and a TIZP, we set up a linear optical pulse compression experiment. An illustration of the conducted experiment is shown in Fig. 1. Light from a continuous-wave (CW) laser at a wavelength of 1,549.706 nm is amplified and sent through a 40-GHz EOIM ($V_\pi$ =3.9 V), which is driven by the electronic waveform generated by a 24 Gsamples/s AWG and amplified by a 12.5-GHz electronic amplifier. The laser provides the same average power (10 mW) for the two reported experiments using a TIZP and a TAZP, respectively. The modulated light is sent through a reflective linearly chirped fiber Bragg grating (LCFBG, working from 1548.91 nm to 1552.52 nm), which introduces a

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predominantly 1st-order dispersion of –10,000 ps/nm. After dispersion, the output temporal waveform is measured with a 45-GHz photo-detector coupled to an electronic sampling oscilloscope.

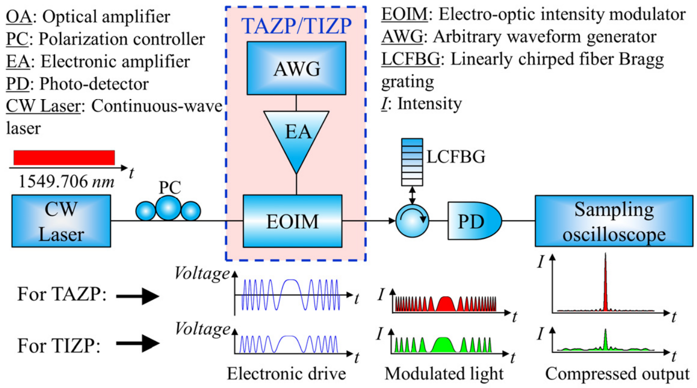


Fig. 1. Experimental scheme for linear optical pulse compression using the TAZP and the TIZP, with the terminology used in the text.

Fig. 2 shows experimental results for the TAZP [top figures: (a), (c), (e), (g)] and the TIZP [bottom figures: (b), (d), (f), (h)]. As shown in Eqs. (1) and (2), the electronic waveforms for a TAZP and a TIZP have the same modulation frequency chirp and they are generated by the same AWG, thus similar distortions between the measured electronic waveforms and the numerically calculated curves are observed for the two cases, see results in Figs. 2(a) and 2(b). After sending the electronic waveforms through the EOIM, amplitude modulation for the TAZP and intensity modulation for the TIZP are realized. The intensity of the measured and the calculated modulated optical waveforms for the TAZP and the TIZP are shown in Figs. 2(c) and 2(d), respectively. The corresponding measured compressed outputs are shown in Figs. 2(e-h). There is an excellent agreement between the numerical simulation and the experiment. In particular, the output pulse in the TAZP experiment [Fig. 2(e)] has a 1.96 times larger peak power and a significantly reduced noise background than those obtained in the TIZP experiment [Fig. 2(f)]. Correspondingly, a smoother spectrum is also observed for the pulse generated in the TAZP experiment, as shown in Figs. 2(g) and 2(h). Considering that the central portions (main lobes) of the output pulses in the two experiments are nearly identical, we estimate that the TZAP offers an energy efficiency improvement by ~96 % with respect to that provided by the TIZP. This energy-efficiency improvement is still lower than that theoretically predicted: discrepancies may be attributed to the limited temporal aperture and the distortions between the measured modulation waveforms and the numerically calculated curves.

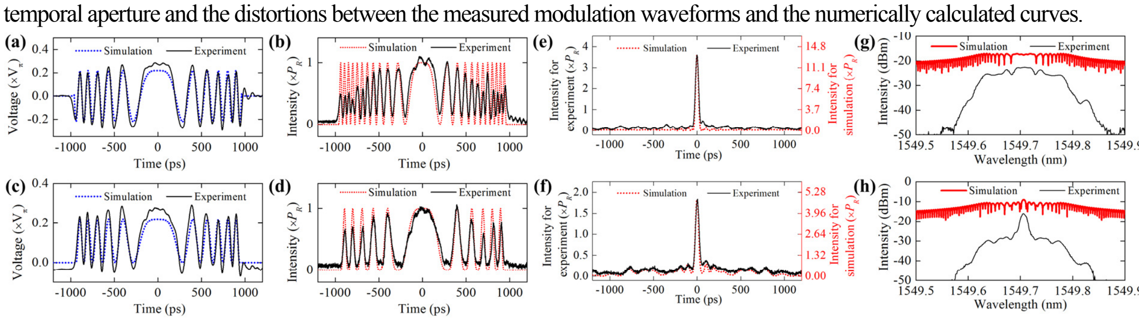


Fig. 2. Experimental and numerically calculated results for linear optical pulse compression based on a TAZP [top figures: (a), (c), (e), (g)] and a TIZP [bottom figures: (b), (d), (f), (h)]. (a), (b), Electronic drives for the modulator. (c), (d), Modulated optical waveforms, where the peak power is $P_R$. (e), (f), Temporal intensity profiles of compressed outputs, which have higher peak powers than $P_R$. The discrepancy between simulation and experiment is due to the insertion loss of LCFBG (~2.77 dB) and the distortions between the measured modulation waveforms and the numerically calculated curves [see (a)-(d)]. (g), (h), Spectra of compressed outputs. The results of simulation in (g, h) are shifted to avoid overlapping the experimental results.

In summary, a novel temporal zone plate based on temporal amplitude modulation has been introduced and investigated. This novel temporal zone plate effectively improves the light-collecting efficiency and noise background performance of previous temporal zone plate designs, while using an identical setup. Efficient temporal zone plates should prove particularly interesting for linear pulse generation and compression experiments and other related applications.

## References

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