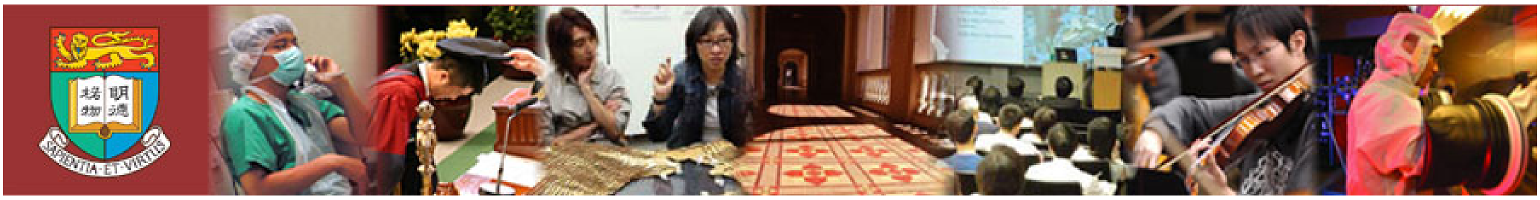

Title	**Comparison of time-lens configurations under different repetition rate**
Author(s)	**Zhang, C; Chui, PC; Wong, KKY**
Citation	**The 10th Conference on Lasers and Electro-Optics Pacific Rim and the 18th OptoElectronics and Communications Conference/Photonics in Switchin (CLEO-PR & OECC/PS 2013), Kyoto, Japan, 30 June-04 July 2013.**
Issued Date	**2013**
URL	**http://hdl.handle.net/10722/189819**
Rights	**OptoElectronics and Communications Conference and Photonics in Switching. Copyright © IEEE.**

Comparison Of Time-lens Configurations Under Different Repetition Rate

Chi Zhang, P. C. Chui, and Kenneth K. Y. Wong*
The Photonic Systems Research Laboratory, Department of Electrical and Electronic Engineering
The University of Hong Kong, Pokfulam Road, Hong Kong
Email: kywong@eee.hku.hk

Abstract

We review the theoretical models and the performance of two existing time-lens configurations, and compare them under different repetition rate in different aspects: the focal group delay dispersion (GDD), and the temporal numerical aperture (NA).

I. INTRODUCTION

Ever since the discovery of the beauty of space-time duality [1], several methods have been developed to perform the temporal imaging, and they could mainly be classified into two categories: the quadratic signal onto phase modulator [2,3] and the parametric mixer with chirped pump [4,5]. The features of each configuration have been explored and optimized for certain kind of applications, but a thorough and quantitative comparison of these two time-lens configurations is needed, especially in the aspect of different repetition rate requirements. The comparison would be essential for the time-lens design in a systematic approach, so as to optimize applications with different repetition rate, such as ultrafast optical communication and bio-imaging systems.

II. PRINCIPLE OF TWO TIME-LENS CONFIGURATIONS

The foundation of time-lens system is based on the duality between the paraxial diffraction in spatial domain, and narrow-band dispersion in temporal domain [1]. The time-lens is similar to the space-lens, which produces an instantaneous quadratic phase modulation in the real space. As a result, the time-lens can be described by a phase transformation in the form of Φ_f, namely the focal GDD; therefore, the time-lens will introduce the quadratic phase modulation in the time domain:

$$t_f(t) = \exp\left(-i\frac{t^2}{\Phi_f}\right) \tag{1}$$

Owing to the ease of implementation, a quadratic phase modulator could be the prime candidate for the time-lens (Fig. 1(a)) [2,3]; however, only the cusp of the sinusoidal signal could approximate the parabolic shape, as shown in Fig. 1(b). We can obtain the focal GDD:

$$\Phi_{f\_PM} = \frac{V_\pi}{2\pi V \omega_m^2} \tag{2}$$

Here, Φ_{f_PM} is determined by frequency of sinusoidal signal ω_m and the voltage added on the phase modulator. Another configuration based on all-optical frequency mixing procedure, and new frequency is a combination of the input frequency and a linear chirped pump frequency, with certain mathematical relation [4,5]. In this paper, a parametric mixing procedure called degenerated four-wave mixing (FWM) is discussed, newly generated idler will contain the conjugated phase information of the signal, accompanied by doubled frequency chirp of the pump, as shown in Fig. 1(d), with the focal GDD:

$$\Phi_{f\_FWM} = \frac{L_p \beta_{2p}}{4} \tag{3}$$

Here, L_p is the dispersive fiber length, and β_{2p} is the second derivative of the propagation constant at the pump wavelength. In order to avoid any overlapping between stretched neighboring periods, a filter is required to confine the pulsewidth of the pump within the time period, as shown in Fig. 1(c).

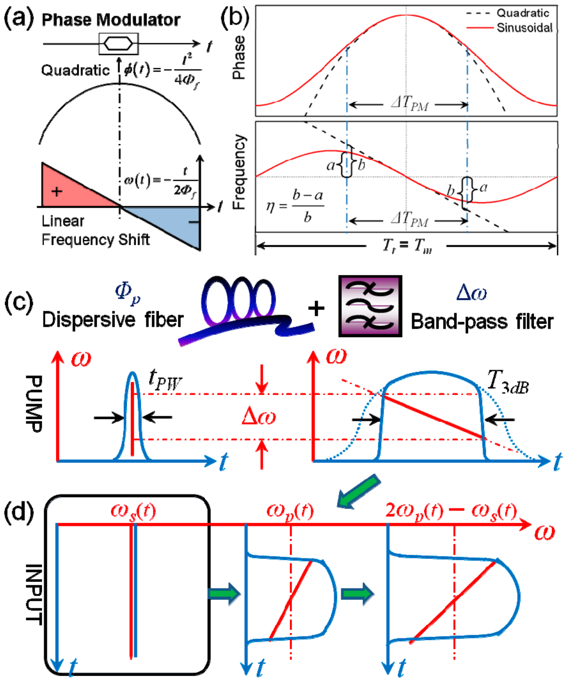

Fig. 1. The principle of performing time-lens by phase modulator and parametric mixer: (a) ideal quadratic signal applied to the phase modulator; (b) the cusp of the sinusoidal signal approximates to quadratic signal, and the corresponding error ratio η; (c) generation of the chirped pump; (d) frequency transformation during the FWM process.

III. RESULTS AND DISCUSSION

Both of the phase modulator and parametric mixer based time-lens can introduce the quadratic phase shift (or linear frequency shift), and realize the function of time-lens. In the case of phase modulator, larger driving voltage and higher frequency help to achieve smaller Φ_f; while for the FWM-based parametric mixer, larger pump

GDD will result in larger Φ_f. First, considering the phase modulator based time-lens, the focal GDD is reduced, when increase the driving voltage; while this voltage cannot exceed a maximum value. We can obtain the following constraint:

$$\Phi_{f\_PM} > \frac{V_\pi}{8\pi^3 f_t^2 V_{\max}} \qquad (4)$$

According to the current electro-optic technology, the bandwidth (BW) of the phase modulator is also limited (f_t < 40 GHz). On the other hand, for the parametric mixer based time-lens, the repetition rate is determined by the pump source. It is limited by the minimum filter BW ($\Delta\lambda_{\min}$), and also the relation pump GDD Φ_p should be larger than the Rayleigh dispersion Φ_{Rp}, then we will have the repetition rate constraint for the parametric mixer:

$$\frac{t_{PW}^2}{8\ln 2} = \frac{\Phi_{Rp}}{2} < \Phi_{f\_FWM} < \frac{\lambda_0^2}{8\pi c f_t \Delta\lambda_{\min}} \qquad (5)$$

The relations shown in Eq. (4) and (5) are plotted out in Fig. 2(a). Generally speaking, the phase modulator only works in higher repetition rate (within the electrical BW); while for the parametric mixer, it can achieve smaller Φ_f across the whole repetition rate range, even beyond the electrical BW. Some previous time-lens works are classified into two groups by different chirping configurations in Fig. 2(a), the phase modulator (red circle) and the parametric mixer (black diamond), which are almost located within these two areas.

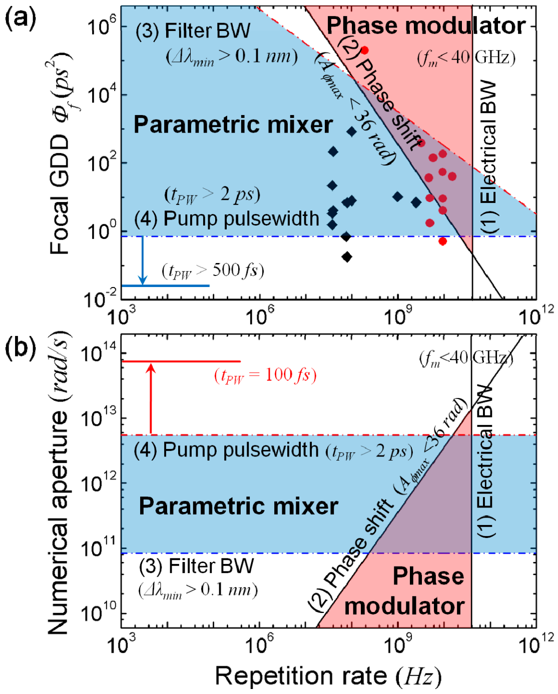

Fig. 2. The effects of repetition rate for two time-lens configurations: (a) the focal GDD distribution due to repetition rate, two sets of dots correspond to the classification of some previous time-lens works; (b) the temporal NA performance changes with different repetition rate.

In spatial optics, the NA characterizes the range of angles over which the system can accept or emit light; while in the time-lens, we can also define NA$_t$ as the allowable range of chirped frequencies. Substituting the focal length by the focal GDD Φ_f, we can then obtain the NA$_t$ = $\Delta T/2\Phi_f$, which just corresponds to the chirped frequency range. Considering the limitations of the focal GDD, we could also obtain the NA$_t$ relation with the repetition rate, as shown in Fig. 2(b). Higher NA$_t$ is achieved in higher repetition rate for the phase modulator; while for the parametric mixer, its NA$_t$ is only determined by the pump pulsewidth and the filter BW.

In general, smaller Φ_f of the parametric mixer usually introduces larger NA$_t$, which will achieve sharper imaging features, but the filter used to avoid the overlapping under higher repetition rate will degrade its performance; while for the phase modulator, larger NA$_t$ and improved resolution is achieved under higher repetition rate. Moreover, large NA$_t$ also makes the parametric mixer easy to misfocus, and the adjustment of the dispersive fiber length is more difficult than increasing voltage applied on the phase modulator. On the other hand, the sinusoidal phase modulator introduces order-of-magnitude higher aberrations than the higher-order dispersion in the parametric mixer.

IV. CONCLUSIONS

In summary, these two time-lens configurations are compared in different aspects, including the focal GDD Φ_f and the temporal NA, and all of them have been associated with repetition rate f_t. Different applications have different requirements in the repetition rate. For example, it is common to use *kilohertz* or *megahertz* in bio-imaging applications, within this range, larger chirped rate and wider frequency range could be achieved in parametric mixer, as shown in Fig. 2(a). At the higher repetition rate, usually referred as optical communication system, these two kinds of time-lens joined together, and both of them can be employed in the overlapping area, other parameters like the effective time duty ratio and the temporal NA will determine the choice of the time-lens configuration.

ACKNOWLEDGMENT

This work was supported by *Research Grants Council* of the Hong Kong Special Administrative Region, China (Project No. HKU 717212E).

REFERENCES

[1] B. H. Kolner, "Space-Time Duality and the Theory of Temporal Imaging," *IEEE J. Quantum Electron.* **30**, 1951-1963, 1994.

[2] C. F. Buhrer, D. Baird, and E. M. Conwell, "Optical Frequency Shifting by Electro-optic Effect," *Appl. Phys. Lett.* **1**, 46-49, 1962.

[3] B. H. Kolner, "Active pulse compression using an integrated electro-optic phase modulator," *Appl. Phys. Lett.* **52**, 1122-1124, 1988.

[4] C. V. Bennett, " Principles of Parametric Temporal Imaging–Part I: System Configurations," *IEEE J. Quantum Electron.* **36**, 430-437, 2000.

[5] C. V. Bennett, " Principles of Parametric Temporal Imaging–Part II: System Performance," *IEEE J. Quantum Electron.* **36**, 649-655, 2000.