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<td>Zhang, C; Wong, KKY</td>
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A Versatile Parametric Spectro-Temporal Analyzer

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

Abstract — We present an ultrafast optical spectrum analyzer with flexible observation range (telescope/wide-angle PASTA), achieves the sharpest resolution of 5 pm (<1 GHz), and the widest observation range of 9 nm, with 100-MHz frame rate.

Keywords — nonlinear optics; four-wave mixing; dispersion; ultrafast spectroscopy

I. INTRODUCTION

Real-time spectrum analyzer is an essential tool in observing ultrafast phenomena. However, previous dispersive approaches are either too slow (by mechanical rotation of a grating [1]), or too restrictive on the input condition (by stretching the spectrum along the fiber [2]). In view of these constraints, we proposed a real-time spectrum analyzer called parametric spectro-temporal analyzer (PASTA), which achieves a frame rate as high as 100 MHz and accommodates various input conditions [3]. In this paper, we explore the PASTA in the context of its observation range. In particular, we realize 17 times optical spectrum zoom in/out ratio by using a pair of time-lenses. As an analogy to the space-lens system, we call these mechanisms telescope/wide-angle PASTA, with 8-dB improvement of the detection sensitivity. As a proof of concept and also for the first time, we demonstrate the sharpest resolution of 5 pm (<1 GHz), and the widest observation range of 9 nm, with 100-MHz frame rate.

II. PRINCIPLE AND EXPERIMENTAL SETUP

Ever since the discovery of the space-time duality between two apparently disparate physical phenomena, the paraxial diffraction and the narrow-band dispersion help to shed new light and understanding on each other [4]. To enlarge the spectral observation range (zoom in/out) in the temporal domain, we may also resort to its spatial counterpart, the camera system as shown in Fig. 1(a). In fact, we can draw the analogy of the pinhole camera with the ADFT, and the single-lens camera with the PASTA. Similarly, if we can implement a pair of time-lenses as in the telescope/wide-angle camera, the observation range of the PASTA will be greatly enhanced. Figure 1(b) and (c) show the step by step changes of the wavelength-to-time relation through the telescope/wide-angle PASTA process.

There are two time-lenses involved in the telescope/wide-angle PASTA, and they are implemented by two stages of four-wave mixing (FWM). A pulse source (2-ps pulsewidth) passing through different pump dispersions are provided as the swept-pumps for two FWMs [5]. Slightly different from the single-lens PASTA configuration, where the second stage FWM pumped by a CW source was only acted as a spectral mirror. In the case of the telescope/wide-angle PASTA, the distance between two lenses (the mid-span dispersion) is critical to control the wavelength-to-time ratio. The overall setup can be simply viewed as two time-lenses \( \Phi_f = \phi_f/2 \) and \( \Phi_m = \phi_m/2 \) inserted with a mid-span dispersion \( \Phi_m \) and followed by the output dispersion \( \Phi_o \), as shown in Fig. 2. The time-lens focusing mechanism requires these four GDD values satisfied certain relation: \( 1/(\phi_f + \phi_m) - 1/\phi_f = 1/\phi_m \), and the zoom in/out ratio is also determined by these dispersions: \( G = \phi_f/(\phi_f + \phi_m) \).

III. RESULTS AND DISCUSSIONS

![Figure 1](image-url). The principle of the telescope/wide-angle PASTA. (a) Temporal ray diagram shows the analogy between the time-lens and the space-lens counterparts. (b) & (c) The signal wavelength-to-time relation changes step by step through the telescope/wide-angle PASTA process.
Figure 2. Detailed experimental setup. Two time-lenses are implemented by FWM based parametric mixer.

Figure 3. Characterization of PASTAs, with 4 equally spaced CW sources.

Although PASTA can capture dynamic spectrum evolution with 100-MHz frame rate [3], the stationary CW source is easier to quantitatively characterize this single-shot imaging. Although there is a 20-ps system timing jitter, the overall accuracy will not be degraded, since the whole frame is shifted synchronously within a single-shot spectrum. The stationary performance of the PASTA configurations measured from the CW source is shown in Table I. First, the telescope PASTA has much larger timing jitter (400 ps), because the timing jitter of the swept-pump was enlarged during the spectral zoom-in process. Second, the telescope/wide-angle PASTA shows 8-dB better detection sensitivity than that of the single-lens PASTA. Because in the single-lens PASTA, the second stage FWM was pumped by a CW source, lower stimulated Brillouin scattering (SBS) threshold limited its conversion efficiency [6]. Figure 3 shows the PASTA traces compared with the conventional OSA (Agilent 86142B) for 4 approximately equally spaced CW sources, and all these configurations show better resolution over the OSA (0.06 nm).

IV. CONCLUSION

In this paper, we present, for the first time, single-shot spectrum measurements of dynamic spectrum using a pair of time-lenses achieved 17 times optical zoom in/out ratio with frame rate of 100 MHz. These PASTA configurations greatly relax the input conditions of the signal under test, arbitrary waveform across the observation window and without the need for synchronization. This approach is particularly suitable to observe non-repetitive spectrum or even unstable spectrum for its dynamic process, without the need for any post-processing. The whole set of PASTA configurations provide a flexible and ultrafast spectrum observation method, and we therefore expect that this approach is the basis of some imaging applications in areas where rapid spectral acquisition is essential.

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