Ultrafast Time Scale Transformation and Recording Utilizing Parametric Temporal Imaging

(Invited Paper)

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Abstract—Parametric temporal imaging enables real time transformation of ultrafast waveforms to a time scale accessible by convention recording instruments. Principles and the development of this technology will be reviewed along with recent experimental results.

I. INTRODUCTION

Single-shot transient recording of ultrafast waveforms is especially challenging when high dynamic range or high repetition rate is required. Temporal imaging [1]–[4] is a signal manipulation technique producing a time scaled replica of an input waveform in a manner directly analogous to that of spatial imaging. Signals can be magnified or compressed in time while maintaining their overall shape. Early work in temporal imaging, [3], [5] and a related time stretching technique [6], utilize an electro-optic time lens and are limited in bandwidth. Parametric temporal imaging [7]–[11] utilizes an all optical time lens process which can impart many THz of bandwidth and have a temporal resolution (step or impulse response duration) < 100 fs. The process works real time, without repetitive sampling. This technology has therefore been pursued as a mechanism to transform waveforms with complex ultrafast detail to a time scale compatible with conventional recording instruments. A review of this technology is presented along with recent results from an all guided wave parametric temporal imaging system [12].

A parametric temporal imaging system is constructed by cascading: (1) an input group delay dispersion (GDD); (2) imparting of a broadband quadratic temporal phase (a linear frequency chirp) through mixing with a chirped pump pulse in a nonlinear crystal; and (3) further GDD. This process is similar to spatial imaging, with dispersion replacing diffraction and the quadratic phase modulation of a lens occurring in time. A focal GDD, $\phi_f'' = -(d\omega/d\tau)^{-1}$, is defined by the amount of GDD required to remove the quadratic phase imparted by the time lens. When an input $A(\tau)$ passes through input GDD ϕ_1'' , a time lens characterized by ϕ_f'' , and output GDD ϕ_2'' , balanced according to the imaging condition $1/\phi_1'' + 1/\phi_2'' = 1/\phi_f''$, a scaled replica $A(\tau/M)$ will emerge with time magnification $M = -\phi_2''/\phi_1''$.

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Early parametric temporal imaging demonstrated $-12\times$ magnification of a 100 Gb/s 1101 pulse pattern and had ≈ 5 ps resolution for the 40 ps pattern [7]. Later work demonstrated $+103\times$ time magnification with < 300 fs resolution but was limited to a 7 ps input record length [8], [9]. Both systems had limited record length, very poor single-shot signal-to-noise ratio (published results were generally repetitively averaged sampling-scope measurements), and were built from bulky and unstable free-space components.

Recent work has improved the record length and signal-to-noise using compact and robust guided-wave technologies [12]. The time lens has a 1.5 THz bandwidth and should ideally be capable of 300 fs resolution. The optical amplifiers, improved efficiency of the aperiodically poled lithium niobate (APPLN) waveguide mixing crystal [13], and the high dispersion-to-loss ratio of the fibers and chirped fiber Bragg gratings (FBG) [14] in this system has lead to an increase in record length to 100 ps and approximately $100\times$ increase in signal-to-noise over the previous work [8], [9], enabling true single-shot performance. The output was recorded on a streak camera for high dynamic range single event applications, and with a photodiode and oscilloscope for high repetition rate applications, with substantially better performance than could be obtained with either recorder technology alone.

II. EXPERIMENT DESCRIPTION

Fig. 1: The main components of the guided-wave parametric temporal imaging system. Multiple input test patterns and output recorders were used.

The system in Fig. 1 was designed for a 100 ps record length and $-33\times$ magnification. The input at 1534 nm is dispersed and amplified in a fiber system designed for $\phi_1'' = -9.611$ ps². The pump is a modelocked fiber laser and soliton compression system producing 12 nm FWHM pulses at 1558 nm. Pulses are picked with a modulator, dispersed, and amplified to between 2.5 and 7 nJ/pulse in a multi-stage amplifier before

combining with the input signal and sum-frequency mixing in an APPLN waveguide. The time lens pump was designed for $\phi_f'' = -9.329 \text{ ps}^2$. A 30 cm long continuously chirped FBG produced $\phi_2'' = -317.2 \text{ ps}^2$ for the sum-frequency at 773 nm. The output is then either recorded on a streak camera, or with a high-speed photodetector and real-time scope.

III. RESULTS AND DISCUSSION

Fig. 2: Time magnified streak camera recordings of “ring-down” patterns with varying delays between 2.0 ps fwhm pulses. At 2 ps apart bumps show on the decaying edge. At a 4 ps spacing dips between pulses are resolved.

Input test patterns for Fig. 2 were “ring-downs” produced by sending a train of 2.0 ps fwhm pulses through a fiber 2×2 splitter and looping an output back to an input with a time delay set slightly different than the laser period. Time magnification was calibrated by making precise changes to the input delay and observing the corresponding $-30.1\times$ output change. The top time scale is that of the streak camera and the bottom is an equivalent input time calculated by dividing by the observed magnification. The recorded output pulses indicate 2.7 ps fwhm pulses at the input, a blurring due to a system impulse response, referenced back to the input, of 1.8 ps, $10\times$ better than the streak camera alone. A noise background on the left side of Fig. 2 is due to unwanted pump second harmonic in band with the desired signal-pump sum-frequency. With this removed, the right side indicates nearly 1000:1 dynamic range.

The input test pattern corresponding to Fig. 3 was created by dispersing a 229 GHz fwhm pulse to 111 ps fwhm using an optical fiber spool and adding a CW reference tuned to the edge of the pulses spectrum. The CW reference and the chirped pulse create a chirped heterodyne beat sweeping in frequency at the chirp rate of the pulse. The magnified output was recorded with a fast photodetector and an 8 GHz Tektronix 6804B scope (Fig. 3 left axis). The right axes are the local beat frequency. A -3.45 GHz/ns chirped beat recorded at the output, times M^2 , indicates a $(312.9 \text{ GHz})/(100 \text{ ps})$ frequency chirp on the input waveform. This single-shot measurement is performed at up to a 155 MHz repetition rate, until the scope’s memory is full.

IV. CONCLUSION

Parametric temporal imaging has been developed as a time scale transformation technique, enabling single-shot recording of ultrafast waveforms on slower conventional recording

Fig. 3: A 229 GHz fwhm chirped heterodyne beat signal, time magnified, and recorded on an 8 GHz real-time scope.

instruments. A system with $-30.1\times$ time magnification has been mated with two final recorders, a streak camera and a real time scope, enhancing the performance of each. Nearly 1000:1 dynamic range recording with 1.8 ps resolution was demonstrated with a time magnified streak camera recorder. Temporal imaging also enabled high repetition rate recording of signals with up to 240 GHz detail using an 8 GHz scope.

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