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All-optical temporal random pattern generation based on photonic time-stretch

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ABSTRACT

We propose a novel all-optical temporal random pattern generation scheme based on photonic time stretch involving cascaded Mach-Zehnder interferometers (MZIs) with different chirped spectral response. The overall spectral response represents a broadband random spectral pattern. Temporal random patterns can then be generated thanks to photonic time stretch which mirrors spectrum encoding to temporal waveform. Tuning of the generated temporal patterns is achieved using a rapidly tunable optical delay module in one of the MZIs.

Keywords: *Chromatic dispersion, Mach-Zehnder interferometer, photonic time stretch, random pattern generation, time delay*

1. INTRODUCTION

Optical random patterns are widely used in optical communications especially in encryption for security, to estimate the bit error rate of a communication system and in compressed signal processing to explore and utilize the signal sparsity. Optical random patterns are traditionally generated by modulating optical carriers with electronically generated random patterns using electro-optic modulator. The main difficulties are high cost and limited bandwidth in generating high speed electronic pseudo-random bit sequences (PRBS).

As a promising solution, all-optical random pattern generation has recently attracted great research interest. For example, this problem have been addressed by generating random numbers based on chaotic nature in lasers [1]. However, the random sequences generated by this method are not non-repeatable and non-predictable. Repeatable optical random patterns have been generated using a spatial light modulator based on space-to-time mapping [2]. But the tuning speed of this system is limited. In [3], there was a proposal for all optical PRBS pattern generation, which however required high speed optical clock signal along with complicated dual-drive differential Mach-Zehnder modulator (MZM).

In this paper, we propose a novel all-optical temporal random pattern generation method which eliminates the need for high speed MZM or high speed electronic PRBS generator. This is made possible based on random spectral filtering and photonic time stretch. In our system, two cascaded Mach-Zehnder interferometers (MZIs) produce overall spectral response representing a broadband random spectral pattern. Chromatic dispersion stretches spectrally shaped ultrashort optical pulses to a random temporal pattern thanks to spectrum-to-time mapping [4]. Fast tuning of the generated optical patterns can be achieved by using a rapidly tunable optical delay module in one of the MZIs.

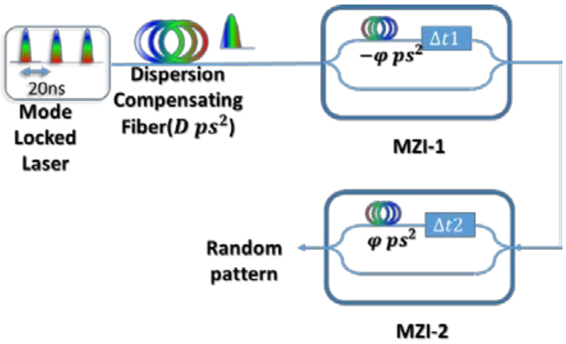


Fig.1. Conceptual diagram of proposed experimental setup for all-optical random pattern generation.

2. PRINCIPLE

The proposed set up is shown in Fig. 1. A mode-locked laser (MLL) is used to generate optical pulses at 50MHz rate with a full-width half-maximum (FWHM) pulse width of 800 fs. After passing through a dispersion compensating fiber (DCF) with dispersion value of D (ps^2), the pulse will be stretched in time leading to spectrum-to-time mapping because of higher dispersion as per temporal far-field Fraunhofer condition [4]. The stretched optical pulses can then be passed through a MZI which has a chirped spectral response due to unbalanced dispersion in two interference arms [5]. The spectral transfer function of MZI-1 can be written as,

$$H_1(\omega)=\frac{1}{2}\left[1+\exp\left(-j\omega\Delta t_1+j\frac{\varphi\omega^2}{2}\right)\right] \qquad (1)$$

where Δt_1 is the fixed delay difference between arms and $-\varphi$ is the dispersion unbalance. The chirp rate and free spectral range (FSR) of the MZI filter can be easily tuned by controlling the dispersion unbalance and time delay difference between two arms.

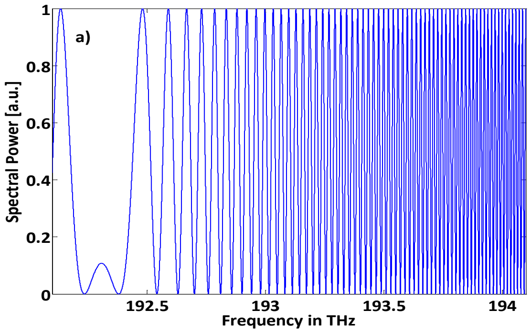
A second cascading MZI has an opposite chirp rate and a tunable delay in one arm. The overall spectral response of the cascaded MZI filter can then be given by

$$\begin{aligned} H(\omega) &= \frac{1}{4}\left[1+\exp\left(-j\omega\Delta t_1 + j\frac{\varphi\omega^2}{2}\right)\right] \\ &\times\left[1+\exp\left(-j\omega\Delta t_2 - j\frac{\varphi\omega^2}{2}\right)\right] \\ &= \frac{1}{2}\exp\left[-j\omega\left(\Delta t_1-\Delta t_2\right)\right]\times \\ &\left[\cos\left[\frac{\varphi\omega^2}{2}+\frac{\omega\left(\Delta t_2-\Delta t_1\right)}{2}\right]+\cos\left[\frac{\omega\left(\Delta t_2+\Delta t_1\right)}{2}\right]\right] \end{aligned} \qquad (2)$$

It can be seen from Eq. (2) that the cascaded MZI has a spectral response showing randomly modulated spectral pattern, which can be controlled by changing the time delay within one of the MZIs. Tuning speed of the optical delay should be matched to the optical pulse repetition rate (tens of MHz). Traditional optical delay lines usually have limited tuning speed of only few kHz. Rapidly tunable optical time delay modules can be achieved by using optical cross switches as mentioned in [6], or reconfigurable optical true time delay method as mentioned in [7].

3. RESULTS

To verify the proposed system, numerical simulations have been performed using VPI-transmission maker with dispersion of the DCF element selected as D = 1274 ps^2, dispersion mismatch in MZIs, φ set to 6.3728 ps^2. The time delay in the first MZI is fixed at Δt_1 = 50 ps , and the second MZI has time delay difference of Δt_2 = 1.25 ps.The individual spectral responses of two cascaded MZIs are shown in Figs. 2.a and 2.b. Opposite chirp rates have been obtained. The broadband optical pulses are spectrally shaped by the cascaded MZIs, with the optical spectrum of the output is shown in 2.c. It can be seen that randomly modulated spectral pattern is achieved. Due to the dispersion-induced spectrum-to-time mapping, an optical temporal random pattern is finally generated, as shown in Fig. 2.d. Perfect mapping between spectrum and time has been achieved.



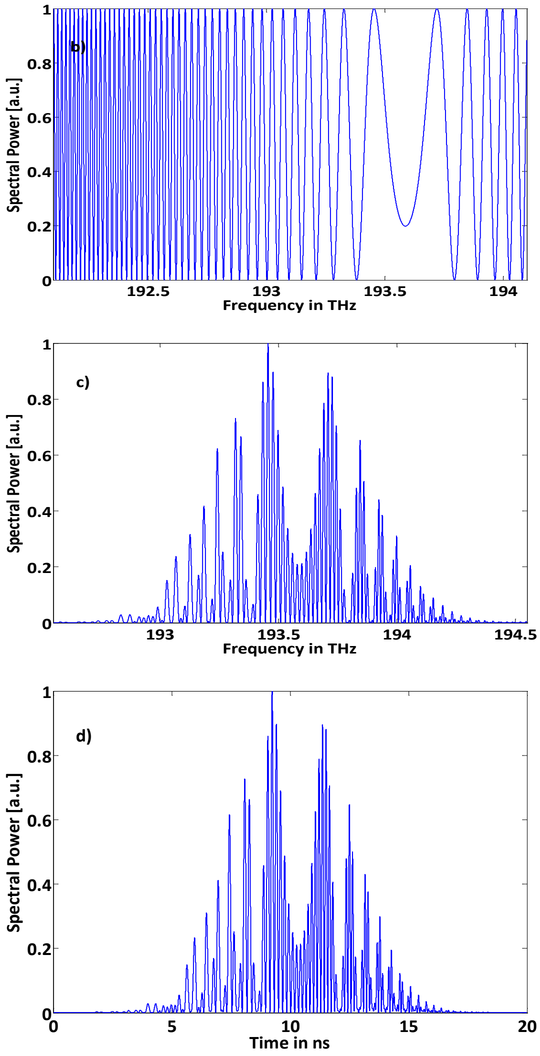
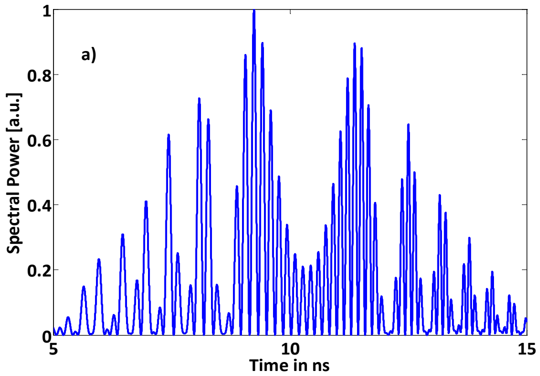


Figure 2. a) Spectral response of the first MZI; b) spectral response of the second MZI; c) Optical spectrum of the shaped optical pulses; d) the generated optical temporal random waveform at the output for Δt_1 = 50 ps , Δt_2 = 1.25 ps.

To demonstrate the tunability and repeatability of the proposed optical random pattern generation, different time delay values in the second MZI have been chosen. Figure 4 show the generated optical random patterns at various delay steps of Δt_2 = 1.25 ps, 10 ps, 17.5 ps, and 25 ps respectively.



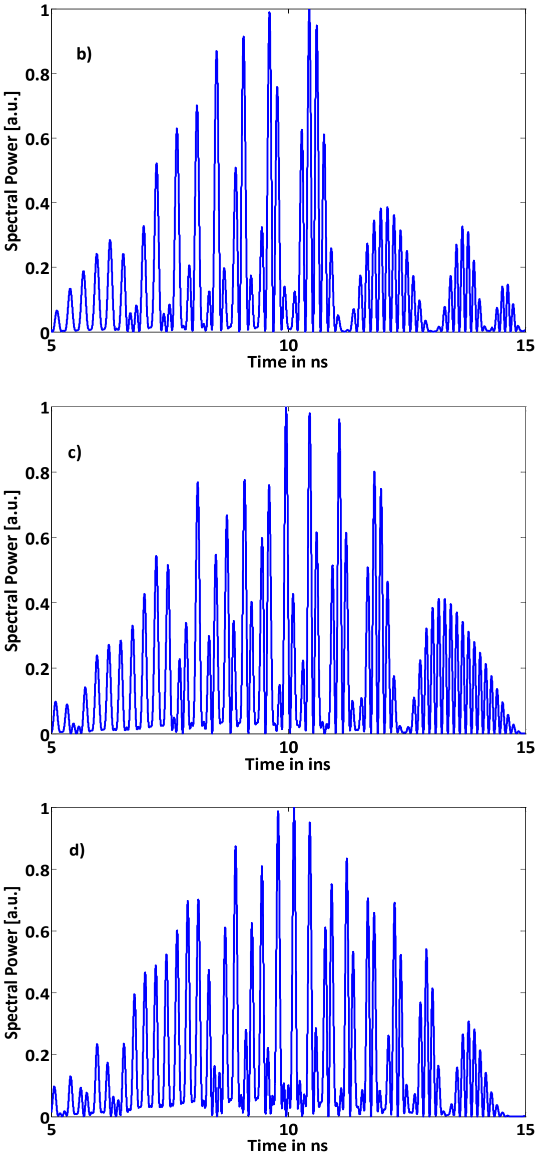


Fig. 4. a) The output temporal waveform at Δt_2 = 1.25 ps b) Δt_2 = 10 ps c) Δt_2 = 17.5 ps d) Δt_2 = 25 ps

To verify the pattern randomness, Fig. 5 shows the correlation Z = corr(X,Y) of one generated random pattern for a specific delay against 19 other patterns generated with different time delays. The X and Y vectors correspond to the total 20 random patterns obtained by tuning the delay Δt_2 from 1.25 ps to 25 ps. X=Y indicates autocorrelation and X $\neq$ Y shows cross correlation. The maximum cross-correlation from this method reaches 63.02% and the average cross correlation is 49.7%.

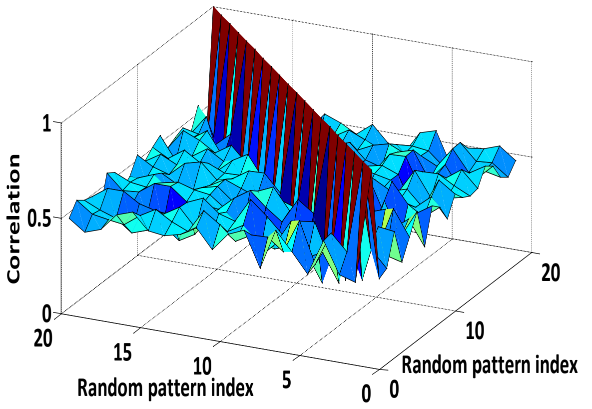


Figure 5. Correlation matrix showing self- and cross-correlation between the generated patterns.

4. CONCLUSIONS

We have proposed and demonstrated a novel all-optical method to generate repeatable all-optical random pattern based on cascaded MZI spectral filtering and photonic time stretch. The technique features simple structure and eliminates the need for expensive high-speed electronic and optoelectronic devices.

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