High Sampling Rate Arbitrary Waveform Generation in the Polarimetric Synthetic Dimension

Yiran Guan[1], Guangying Wang[2], Jiejun Zhang[2], and Jianping Yao[1*]
[1]Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada
[2] Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonics Technology, Jinan University, Guangzhou, 511443, China
** jpyao@uottawa.ca*

Abstract: High sampling rate arbitrary waveforms generated in the polarimetric synthetic dimension based on a fiber-optic system is proposed. A triangular, rectangular, and sawtooth waveform at a sampling rate of 80 GSa/s are experimentally generated.

1. Introduction

High-speed arbitrary waveforms play an important role in various applications, such as optical communications [1], radar [2], and biological imaging [3]. In practice, a state-of-the-art electronic arbitrary waveform generator (AWG) can usually operate at a sampling rate of tens of giga sample per second. To reach such a high speed, however, the electronic instrument usually requires massive interleaving channels due to the limited speed of the electronic analog-to-digital converters (ADCs) in each channel and thus is bulky and expensive [4].

Thanks to the inherent high speed and broad bandwidth offered by modern photonics, photonic generation of arbitrary waveforms has attracted great interest in recent years and is expected to break the speed limit induced by electronic ADCs in purely electronic AWGs. Extensive works have also been made to generate microwave arbitrary waveforms based on free-space or fiber optics, such as wavefront shaping [5], spectral shaping [6], wavelength-to-time mapping [6], and optoelectronic oscillation [7]. However, the speeds of the generated microwave waveforms are still limited by the bandwidths of electro-optical modulators to tens of gigahertz [8].

The synthetic dimension provides additional dimensions in a unitary physical system, allowing the complex manipulation of a field or particle to explore higher dimensional phenomena [9]. Recently, the synthetic dimension has been introduced to the photonics field in which different optical parameters, such as time [10], frequency [11], and orbital angular momentum are manipulated [12]. In our previous work, we showed that the photonic synthetic dimension can transform technical challenges between dimensionalities. We proposed a dual-loop fiber-optic system and experimentally demonstrated the generation of a fully reconfigurable arbitrary waveform with a sampling rate of up to 1.64 TSa/s in a temporal synthetic dimension [13]. However, the dual-loop system is bulky, complicated, and has poor stability.

In this work, we propose and experimentally demonstrate a novel approach to photonic generation of arbitrary waveforms in the polarimetric synthetic dimension with an ultra-high sampling rate by using a polarization modulator (PolM) in a polarization maintaining fiber (PMF) loop. An optical seed pulse produced by a mode-locked laser (MLL) source is directed into the PolM, in which the polarization state of the optical pulse is controlled by a driving signal applied to the PolM. Then, the seed pulse with a designed polarization state recirculates in the PMF loop. Due to the birefringence, the refractive indices of the PMF in the x- and y-polarization axes (fast and slow axes), n_x and n_y, are slightly different. Thus, a single seed pulse is split into two pulses, with one having an x-polarization and the other a y-polarization, which results in the implementation of the polarimetric synthetic dimension. The temporal interval between the two pulses depends on the length of the PMF. The amplitudes of the two pulses are controlled by the polarization angle of the seed pulse after the PolM. Then, the two pulses are redirected into the PolM for the second round trip and will be split into three pulses. After multiple round trips, a pulse burst with a given pulse interval and a designated amplitude profile is produced, leading to the generation of a sampled arbitrary waveform. The approach is demonstrated experimentally. A triangular, rectangular, and sawtooth waveform with a sampling rate of 80 GSa/s are generated. The generated waveforms show high fidelity with an average root-mean-square error (RMSE) as low as 0.0652.

2. Principle

Figure 1 shows the proposed AWG. It consists of a single PMF loop incorporating a PolM. An optical pulse train is generated by a MLL with a repetition rate of 48 MHz and a seed pulse from this pulse train is selected by using a Mach-Zehnder modulator (MZM) as a gate controlled by an electrical pulse from an AWG. A polarization controller (PC1) is connected before the MZM to minimize polarization-dependent loss. Before the seed pulse is directed into the PolM, a second PC (PC2) is placed between the MZM and the PolM to ensure that the injected seed pulse has a linear polarization state with an angle of 45° relative to one principal axis of the PolM. In the PolM, the polarization state of the seed pulse is rotated by an angle of θ by a specific voltage applied to the PolM. Then, the seed pulse is injected into the PMF loop, with refractive indices, n_x and n_y, for the x- and y-polarization axes, resulting in the different group velocities along the x- and y-polarization axes. The single seed pulse with a designed polarization angle will split into two pulses, $u_{1,1}$ and $v_{1,1}$, with two different amplitudes along the x- and y-polarization axes, respectively, as shown in Fig. 1(b). The optical pulses at the m-th round trip and n-th temporal position along the x- and y-polarization axes are given by

$$u_{m,n} = \left(u_{m-1,n-1} + v_{m-1,n}\right) \times \cos\left(\theta_m + \frac{\pi}{4}\right) \quad (1.1)$$

$$v_{m,n} = \left(u_{m-1,n-1} + v_{m-1,n}\right) \times \sin\left(\theta_m + \frac{\pi}{4}\right) \quad (1.2)$$

where θ_m denotes the rotation angle induced by the PolM at the m-th round trip. The temporal interval between the two pulses depends on the difference between n_x and n_y, and the length of the PMF loop L_{PMF}, which is given by

$$\Delta t = \left(\frac{n_x - n_y}{c}\right) L_{\mathrm{PMF}} \quad (2)$$

where c is the velocity of light in vacuum. Before the two pulses go back to the PolM, a third PC (PC3) is incorporated before the PolM in the PMF loop to control the polarization state of the recirculating pulses to have an angle of 45° relative to the principal axis of the PolM. Then, the two pulses undergo polarization modulation again in the PolM and are split into three pulses after the second round trip. In the PMF loop, an acousto-optic modulator (AOM) is employed to shift the frequency of a recirculating pulse by 200 MHz for each round trip to avoid lasing. Note that the AOM also works as an optical switch by applying a gate signal to terminate the pulse recirculation in the loop after a target waveform is generated. To ensure the pulses can recirculate in the loop for a sufficiently large number of round trips, an erbium-doped fiber amplifier (EDFA) is incorporated to compensate for the loop loss. To minimize the reduction in the signal-to-noise ratio (SNR), a tunable optical filter (TOF) is connected after the EDFA to remove the amplified spontaneous emission (ASE) noise.

As the seed pulse recirculates in the PMF loop for multiple round trips, a pulse burst $s[n]$ is generated, which is a temporally sampled arbitrary waveform, given by,

$$s[n] = \left|u_{m,n} + v_{m,n+1}\right|^2, \ 0 \le n \le m \quad (3)$$

Finally, the generated optical arbitrary waveform is directed out of the loop through an optical coupler (OC2) and sent to a photodetector (PD) where the optical arbitrary waveform is converted to an electrical arbitrary waveform, which is displayed by a high-speed oscilloscope (OSC).

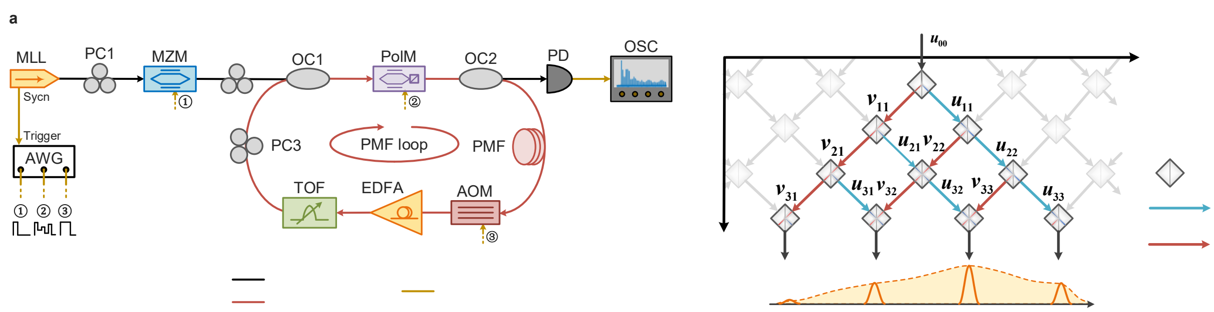

Fig. 1. (a) Schematic diagram of the proposed AWG consisting of a single PMF loop incorporating a PolM. (b) The joint operation of the PolM and the PMF loop results in pulse splitting for each round trip, which constructs the polarization synthetic dimension.

3. Experimental results

An experiment is carried out based on the setup shown in Fig. 1. In the experiment, the PMF loop, consisting of a single mode fiber (SMF) of 45 m and a PMF of 100 m, has a total length of 145 m, corresponding to a round trip time of 0.725 µs. The difference between the refractive indices along the x- and y-polarization axes, n_x and n_y, is 37.5×10^{-6}. Thus, for a seed pulse injected into the loop, the temporal interval between two adjacent pulses at the output of the PMF loop is 12.5 ps. After multiple round trips, a pulse burst is generated, which is directed out of the loop through OC2, as shown in Fig. 2. In the experiment, a waveform with 31 sampling points is generated at the

30th round trip and a gate signal is applied to the AOM to terminate the pulse recirculation in the loop after the 31st round trip. To generate a waveform with a given amplitude profile, a driving signal calculated by a dedicated backpropagation algorithm [13] is applied to the PolM. Fig. 3(a)-(c) shows the driving signals applied to the PolM for the generation of a triangular, rectangular, and sawtooth waveform with 31 sampling points, respectively. Figure 3(d)-(f) shows the experimentally generated triangular, rectangular, and sawtooth waveforms with a sampling rate of 80 GSa/s. The target waveforms are also shown in solid-red lines for comparison. Each sampling point is shown as a red dot. The average RMSE is calculated to be 0.0652, which confirms the high fidelity of the generated arbitrary waveforms. Note that due to the limited bandwidths of the PD and OSC (25 GHz and 36 GHz, respectively), the rectangular and the sawtooth waveforms have relatively slow rise/fall slopes, making the RMSE relatively large.

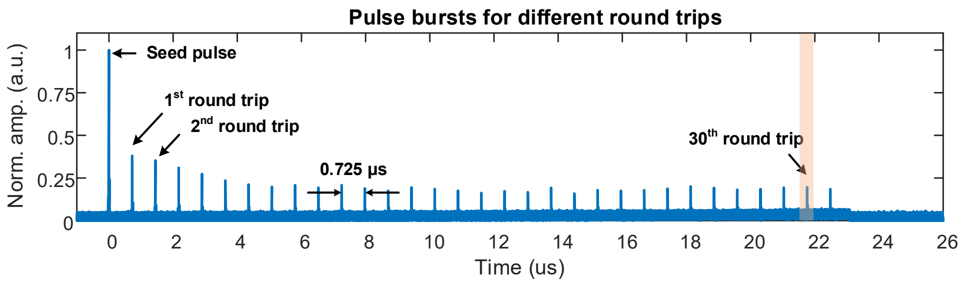

Fig. 2. The pulse bursts at the output of the PMF loop for different round trips. The PMF loop has a total physical length of 145 m or a round trip delay of 0.0725 μs. The pulse bursts after the 31-st round trip are blocked by a gate signal applied to the AOM in the PMF loop.

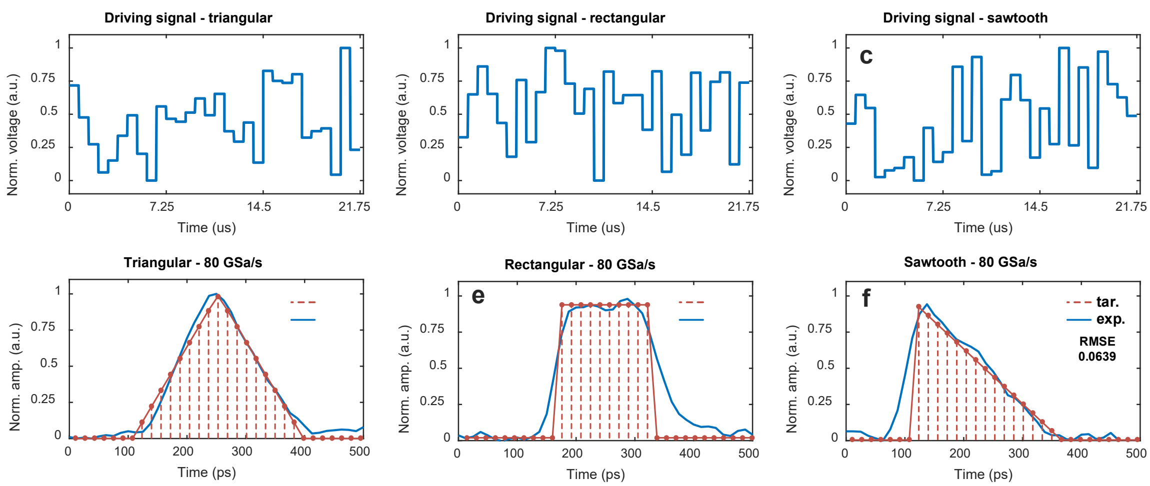

Fig. 3. (a)-(c) Driving signals applied to the PolM. (d)-(f) Experimentally generated triangular, rectangular, and sawtooth waveforms.

4. Conclusion

We have proposed and experimentally demonstrated a novel approach to photonic generation of arbitrary waveforms with an ultra-high sampling rate in the polarimetric synthetic dimension, implemented based on a PMF loop incorporating a PolM. A triangular, rectangular, and sawtooth waveform with a sampling rate of 80 GSa/s were generated. The average RMSE was calculated to be 0.0652, confirming the high fidelity of the generated waveforms. The key advantage of the approach is that a single physical loop was employed to generate arbitrary waveforms at ultra-high sampling rate in the polarimetric synthetic dimension, making the implementation greatly simplified.

Acknowledgments

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

[1] A. B. Carlson, et al., Communication systems. 5th Edition, McGraw-Hill Education, 2010.
[2] A. W. Rihaczek, Principles of high-resolution radar. Norwood, MA: Artech House, 1996.
[3] Y. Liang, et al., *Nat. Commun*., 13 (2022).
[4] J. Meng, et al., *Adv. Photon. Res*., 2 (2020).
[5] M. Veli, et al., *Nat. Commun*., 12, (2021).
[6] H. Chi, et al., *IEEE J. Microwav*., 1, 787-803 (2021).
[7] J. Zhang, et al., *Nat. Commun*., 11 (2020).
[8] D. Renaud, et al., *Nat. Commun*., 14 (2023).
[9] L. Xiao, et al., *Nat. Phys*., 16, 761-766 (2020).
[10] B. Bartlett, et al., *Optica*, 8, 1515-1523 (2021).
[11] S. Buddhiraju, et al., *Nat. Commun*., 12 (2021).
[12] X. W. Luo, et al., *Nat. Commun*., 8 (2017).
[13] Y. Guan, et al., *Commun. Phys*., 6 (2023).