Experimental Demonstration of an Optical Second-Order Volterra Nonlinear Filter using Wave Mixing and Delays to Equalize a 20-Gbaud 4-APSK Channel

Kaiheng Zou[1], Peicheng Liao[1], Huibin Zhou[1], Ahmad Fallahpour[1], Amir Minoofar[1], Ahmed Almaiman[1,2], Fatemeh Alishahi[1], Moshe Tur[3], and Alan E. Willner[1]

1. Dept. of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA
2. King Saud University, Riyadh, 11362, Saudi Arabia
3. School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel

Email: kaihengz@usc.edu

Abstract: We demonstrate an optical second-order Volterra filter using wave mixing and delays. We measure the frequency response and perform the compensation of a nonlinearly distorted 20-Gbaud 4-APSK signal with BER reduction from 8.2×10^{-3} to 3.2×10^{-3}.

1. Introduction

Optical signal processing has the potential to perform various functions on a data signal [1], and an optical tapped-delay-line can perform digital filtering for different applications, such as equalization, correlation, and pulse shaping [2]. Such optical signal processing has the potential advantages of: (i) avoiding inefficient optical-to-electrical-to-optical conversion for a data signal that is in the optical domain, and (ii) high-speed operation on multiple parameters of the optical wave [1].

In general, signal processing relies on ***linear*** filtering to achieve various functions [2]. However, ***nonlinear*** filters can enable higher system performance under many circumstances [3-5]. An example of a nonlinear filter is the Volterra function, and the use of higher-order terms can improve the quality of an output data signal [4,5].

There have been multiple optical approaches to achieve ***linear*** filter signal processing functions [2,6-7]. However, there have been few reports of achieving optical ***nonlinear*** filtering. One reported optical approach used a free-space system to achieve a second-order operator through auto triple correlation, but that approach: (i) only achieved the nonlinear function without the linear term, and (ii) it did not show operation on an actual optical data channel [8].

In this paper, we experimentally demonstrate an optical second-order Volterra nonlinear filter using wave mixing and delays. We measure the first-order and second-order sinusoidal input describing functions of the filter with up to three first-order taps and six second-order taps. We also show using the filter to equalize a nonlinearly distorted 20-Gbaud 4-amplitude and phase shift keying (4-APSK) optical data channel. Using three first-order taps and one second-order tap, the bit error rate (BER) is reduced from 8.2×10^{-3} to 3.2×10^{-3}.

2. Concept

The block diagram of a general second-order Volterra filter is shown in Fig. 1(a). The input signal $x(t)$ is delayed by different amounts of delay, $T_i=i\cdot T$, and each delayed signal is multiplied by the corresponding tap weights h_i, which are the first-order taps. If only these first-order taps are combined at the output, the filter becomes a linear finite impulse response (FIR) filter. In addition, there are second-order taps, which are the multiplication of two delayed signals $x(t\text{-}T_i)$ and $x(t\text{-}T_j)$ together with the tap weight h_{ij}. The output of a second-order Volterra filter is a combination of all these first- and second-order taps. Note that a general Volterra filter can go to higher orders, which involves the taps with multiplication of more delayed signals.

The concept of the optical nonlinear Volterra filter using wave mixing and delays is shown in Fig. 1(b). A frequency comb is used to generate the signal copies and coherent dummy pumps. A programmable liquid crystal on silicon (LCoS) filter can be used to adjust the weights of each tap. In contrast to an FIR filter based on the tapped delay line structure, for which a dispersion element can be used to introduce the tap delays as only the first-order

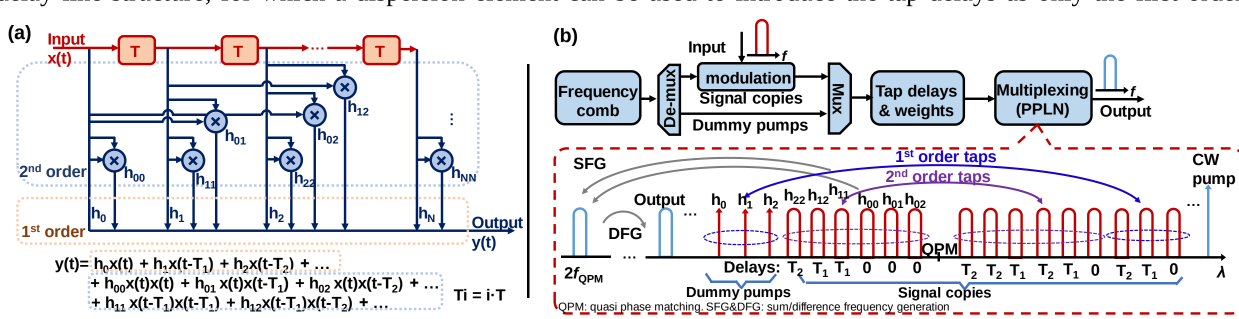

Fig. 1 Concept of (a) Volterra series filter with up to second-order taps; (b) Optical second-order Volterra filter using wave mixing and delays.

taps with tap delays linear to the wavelength are involved. Here, in order to apply the correct delays for the second-order taps, the periodical tap delays regarding to the wavelength are needed. These periodical tap delays could be achieved with some sampled fiber Bragg gratings (FBG). In our later proof-of-concept experiment, the tap delay is also introduced by the LCoS filter for simplification. The taps are multiplexed together though the wave mixing in a periodically poled lithium niobite (PPLN) waveguide. For the first-order taps, the signal copies and the corresponding dummy pumps that are symmetric about the quasi phase matching (QPM) frequency (f_{QPM}) will interact with each other through sum frequency generation (SFG) to generate the mixing terms at $2f_{\mathrm{QPM}}$. For the second-order taps, the signal copies that are symmetric about f_{QPM} also interact with each other to generate the mixing terms at $2f_{\mathrm{QPM}}$. Thus, all the mixing terms are generated at the same frequency. With another continuous-wave (CW) dummy pump sent into the PPLN, an output is generated at the same frequency range with the input signals through difference frequency generation (DFG).

3. Experimental setup

The experimental setup is illustrated in Fig. 2(a). A 20 GHz frequency comb is generated from a mode-locked laser. Several comb lines are selected from the comb source with LCoS 1. The LCoS filter 1 has two output ports. Three comb lines are sent to one port to be used as the dummy pumps. Up to 15 comb lines are sent to the other port to generate the signal copies by using an IQ modulator. Although we only modulate on one constellation axis of the signal here, the nonlinear filter can be applied to both amplitude and phase modulated signals. As we implement up to 3 first-order taps and 6 second-order taps, the 3 dummy pumps and 6 signal copies are chosen to have a spacing of 100 GHz. The other 9 signal copies have the same spacing of 100 GHz. These signal copies and dummy pumps are mutually coherent, but they go through different fibers, resulting in a changing phase difference because of the thermal and acoustic vibration of the fibers. Ideally, this phase difference can be stabilized with a slow feedback loop or by moving the system to an integrated compact device. The generated signal copies and the dummy pumps are combined and the LCoS filter 2 is used to adjust the delays and weights of the taps. The delays of the taps range from 0 ps, 25 ps, to 50 ps. The output of LCoS 2 is then amplified to 1.1 W by a high-power EDFA 2. A laser source at the wavelength of 1560.42 nm is amplified to 0.8 W as another CW pump. They are combined before sent into a PPLN waveguide with the QPM wavelength of 1550.5 nm to generate the multiplexed output through wave mixing. The multiplexed output signal is selected with an optical band-pass filter (BPF) 3. After amplification it is received by a coherent receiver.

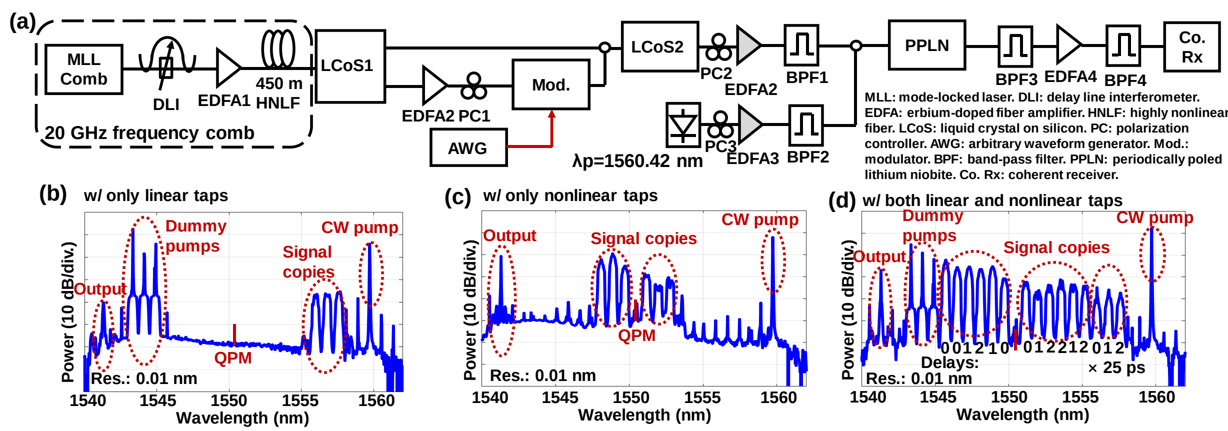

Fig. 2 (a) Experimental setup and (b-d) spectra at the output of PPLN for three different tap configurations.

The optical spectra at the output of the PPLN are shown in Figs. 2(b-d) corresponding to three different cases of the tap configurations. In Fig. 2(b), only the three dummy pumps and the signal copies that are symmetric to the dummy pumps about the QPM are activated. Therefore, the system functions as a 3-tap linear FIR filter. In Fig. 2(c), only the six signal copies are activated for signal and signal mixing, resulting in an output of 3 second-order taps. In Fig. 2(d), all the dummy pumps and signal copies are activated, so that the output is a combination of 3 linear taps and 6 second-order taps. The delays of each signal copies are shown as multiplications of 25 ps.

4. Results and discussion

We first characterize the optical filter by measuring the first-order and second-order sinusoidal input describing functions. The k-th order sinusoidal input describing function $H_k(f)$ is defined as $H_k(f)=Y(kf)/X(f)$, where $Y(f)$ and $X(f)$ are the output and input spectra, respectively. They are the system response at $k{\cdot}f$ frequency when the input is a sinusoidal wave with the frequency of f [9].

The describing functions are measured by sending a frequency sweep sine wave signal as the input to the modulator. The frequency sweeps from 0 to 30 GHz with the step of 0.1 GHz. The measured describing functions are shown in Fig. 3 for different tap configurations. Figures 3(a-b) show describing functions with 2 and 3 first-order taps respectively. Figures 3(c-d) show describing functions with 2 and 3 second-order taps respectively. Figure 3(e) show describing functions with 2 first-order taps and 2 second-order taps together. Finally, Fig. 3(f) show the describing functions with all the 3 first-order taps and 6 second-order taps. The difference between the experimental result and simulation might be because of the imperfect tap weights and delays setting in the experiment compared to the designed ones. When there are more taps, this difference becomes larger.

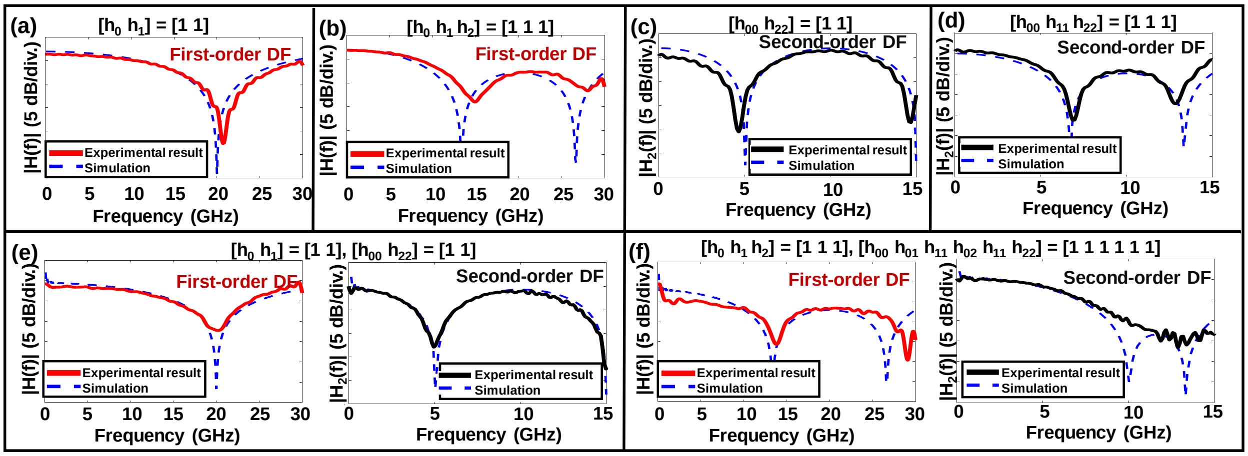

Fig. 3 Measured first-order and second-order sinusoidal input describing functions ($H_1(f)$ and $H_2(f)$) of the system for different tap configurations: (a-b) Only first-order taps. (c-d) Only second-order taps. (e-f) Both first-order and second-order taps. The tap weights of each configuration are shown in the sub-titles. DF: describing function.

We also show the use of the optical nonlinear filter to equalize a nonlinearly distorted 20 Gbaud 4-APSK signal as shown in Fig. 4. The 4-APSK signal is a shifted four-level pulse amplitude modulation (4-PAM) signal without direct current (DC) component. Figure 4(a) shows the received undistorted signal eye diagram which is an evenly distributed 4-PAM signal. We apply a power saturation like nonlinear distortion as shown in Fig. 4(b) to the signal in the AWG, which increases the BER to 0.0082. With a 3 linear tap filter, the BER is decreased to 0.0060 as shown in Fig. 4(d), but the uneven levels cannot be equalized. When second-order taps are used, the received signal is in an unstable state due to the above mentioned thermal and acoustic vibration of the different fibers that the dummy pumps and signal copies go through. The output can be potentially stabilized with a slow feedback loop or integrated devices. We obtained the received signal in some instance that the phase difference between the taps indeed became the desired one. As shown in Fig. 4(e), with one more second-order tap, the levels become more even and the BER can be reduced to 0.0032.

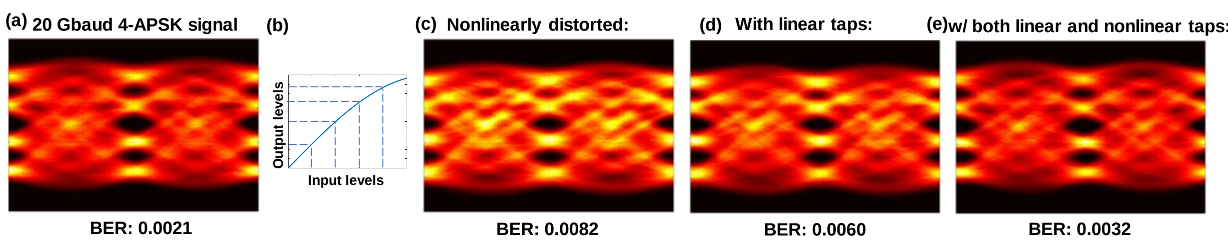

Fig. 4 Compensation of a nonlinearly distorted 20 Gbaud 4-APSK signal. (a) Undistorted 20 Gbaud 4-APSK signal. (b) The power saturation like nonlinear distortion applied to the signal. (c) The distorted signal. (d) Compensated signal with 3 linear taps. (e) Compensated signal with 3 linear taps and 1 second-order tap.

Acknowledgement

We acknowledge the support of AFOSR project (FA9550-15-1-0166), Vannevar Bush Faculty Fellowship from ASD (R&E) and ONR (N00014-16-1-2813).

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