Optics Letters

High-speed and broadband digital receiver based on optical sampling pulse waveform matching

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Received 10 December 2019; revised 6 February 2020; accepted 6 February 2020; posted 6 February 2020 (Doc. ID 385657); published 4 March 2020

In this Letter, we propose a high-speed, broadband photonic digital receiver that can realize the matched filtering of the digital signal through shaping the optical sampling pulse according to the specific waveform of the transmitted digital signal. The receiver's filtering response is matched with the spectrum of the digital signal's specific waveform, and the instantaneous signal-to-average-noise ratio of the filtered signal is maximized at the sampling points. The principle of proposed receiver is theoretically analyzed and experimentally verified. The weak digital signals with different signal-to-noise ratio are detected and correctly distinguished in the experiments.

https://doi.org/10.1364/OL.385657

For the advantages of digital technology in transmission, processing, and storage, digital signal has a wide range of applications in the fields of communications, radar, etc. However, affected by the channel conditions or the requirements such as confidential communication and interference resistance, the signal transmission is usually accompanied by noise. To distinguish the relatively weak signal from the noise in the low signal-to-noise ratio (SNR) case, high-performance analog-to-digital converters (ADCs) are required, which represents one of the major bottlenecks [1]. Especially, for the signal submerged in noise; it cannot be detected and distinguished through direct sampling.

According to the maximum SNR principle, the instantaneous signal-to-average-noise ratio (I-SNR) of the sampled results should be maximized to also maximize the signal detection ability [2]. Based on the prior knowledge of the digital signal's specific waveform, the matched filter whose impulse response is a time reverse of the digital signal's waveform can realize the maximum I-SNR at the sampling points. The existing matched filtering approaches can be mainly divided into two kinds. In the first kind, the received signal is sampled at first and then filtered by a digital matched filter [3]. It needs a high-speed ADC to capture the received signal's waveform, and it brings a huge computing pressure to the backend, especially when the transmission speed is high. In the second kind, the signal filtering is physically realized by a multiplier–integrator cascade circuit in the analog domain [4]. The speed of ADC just needs to be the same as the signal transmission speed, and the backend computation is avoided. However, limited by the bandwidth of the commercial analog multipliers [5], the bandwidth of the multiplier–integrator cascade circuit is limited at hundreds of MHz.

In this Letter, we propose a digital receiver based on optical sampling pulse shaping, which can maximize the I-SNR of the filtered signal at the sampling points, to realize the matched filtering and sampling of the weak digital signal. Benefiting from the merits of broadband photonic devices, the proposed receiver's bandwidth can be improved significantly. With the improved bandwidth, digital signal can be received at a higher transmission rate, which makes the proposed receiver suitable for additional application scenarios. In addition, the wide bandwidth of the receiver allows the transmitted signal power to be distributed in a wider spectrum for interference resistance. The proposed photonic digital receiver is theoretically analyzed and experimentally verified.

Figure 1(a) illustrates the schematic of a digital signal transmitter and the proposed photonic digital receiver based on the optical sampling pulse waveform matching. In the transmitter, the waveform of the binary sequence $\{a_i\}$ is always shaped in the transmitter filtering process and the modulation process. The shaped pulse sequence with specific waveforms is transmitted and affected by the noise in the transmission channel. In the receiver, the received signal, which contains the transmitted signal and noise, modulates the optical sampling pulse train via an electro-optic modulator, which is usually a lithium niobate Mach–Zehnder modulator (MZM). The modulated pulse train is detected by a photodiode (PD) and then filtered by an analog low-pass filter (LPF). Finally, the signal passed through the LPF is quantized by an ADC, and the filtered and digitized results can be directly obtained. Through shaping the optical sampling pulse, the filtering response can be reconfigured flexibly [6–8]. When the optical sampling pulse is shaped according to the specific waveform of the transmitted signal, the whole procedure can be considered as a sampling system with a matched filter of the transmitted signal's waveform, as shown in Fig. 1(b). The received signal can be match filtered, and the I-SNR of the filtered signal can be maximized at the sampling points of the

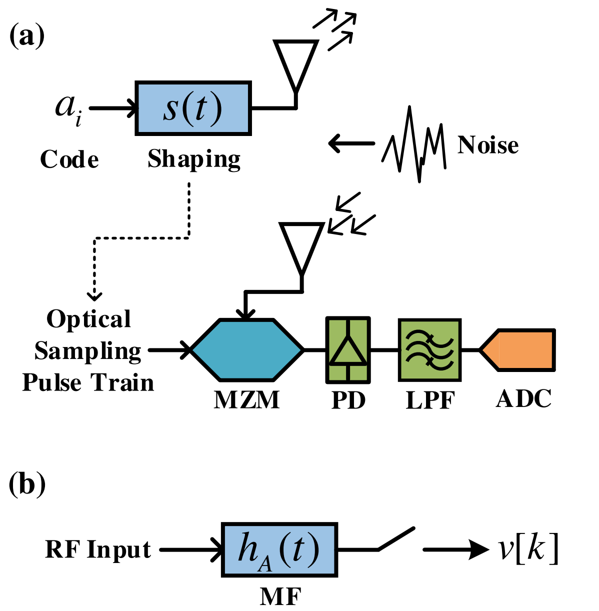

Fig. 1. (a) Digital signal transmitter and the proposed photonic digital receiver. (b) Equivalent model of the proposed photonic digital receiver. MZM, Mach–Zehnder modulator; PD, photodiode; LPF, low-pass filter; ADC, analog-to-digital converter; MF, matched filter.

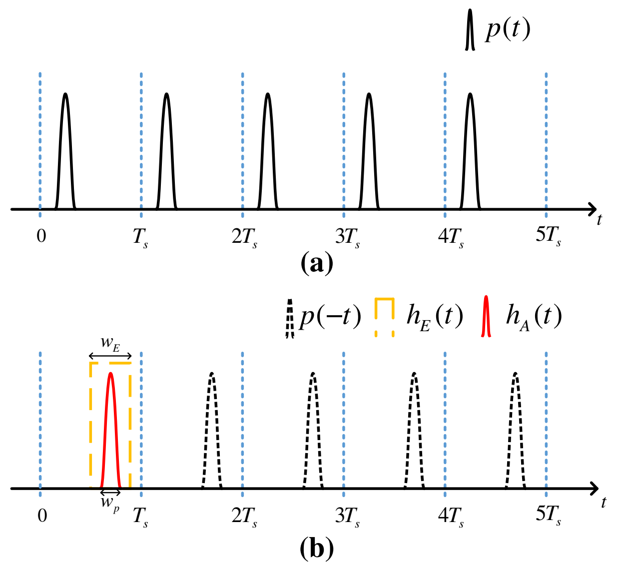

Fig. 2. (a) Schematic of the temporal shape of the optical sampling pulse train. (b) Schematic of the photodetection impulse response, the time-reversed temporal shape of the optical sampling pulse train, and the equivalent impulse response of the proposed photonic digital receiver.

ADC. Through comparing the sampling result and the decision threshold, the binary sequence $\{a_i\}$ can be recovered.

The temporal shape of the received signal $r(t)$, which is composed of the transmitted signal and relatively strong noises, can be expressed as

$$r(t) = \sum_{i=-\infty}^{+\infty} a_i s(t - iT) + n(t), \tag{1}$$

where $a_i = -1/1$, which is corresponding to the digital signal 0 and 1, $s(t)$ is the specific waveform of the digital signal, $1/T$ is the transmission rate, and $n(t)$ is the noise.

According to the prior knowledge of the transmitted signal, the repetition period of the optical sampling pulse train, T_s, is set the same as T, and the optical sampling pulse, $p_s(t)$, is shaped similar as $s(t)$. Hence, the temporal shape of the matched optical sampling pulse train, whose schematic is shown in Fig. 2(a), can be expressed as

$$\begin{aligned} p(t) &= \sum_{m=-\infty}^{+\infty} p_s(t - mT_s) \\ &= P_A \sum_{m=-\infty}^{+\infty} s(t - mT), \end{aligned} \tag{2}$$

where P_A is the average power ratio between the matched optical sampling pulse train and the transmitted signal.

The optical pulse train is modulated by the received signal in the MZM. In the small-signal condition, the response of the MZM biased at quadrature can be approximated linearly, and the modulated component can be expressed as

$$p_M(t) = [r(t) * h_M(t)]\, p(t), \tag{3}$$

where $h_M(t)$ is the small-signal impulse response of the MZM, and * represents the convolution operation. Then the modulated signal is detected by a PD, filtered by an analog LPF, and quantized by an ADC, whose sampling rate is the same as the optical sampling pulse train's repetition rate. The sampling results of the modulated component can be expressed as [9]

$$\begin{aligned} v[k] &= \{[r(t) * h_M(t)]\, p(t)\} * h_E(t)|_{t=kT_s} \\ &= r(t) * h_M(t) * [p(-t) h_E(t)]|_{t=kT_s} \\ &= r(t) * h_M(t) * \left[h_E(t) \sum_{m=-\infty}^{+\infty} p_s(-t - mT) \right]\Bigg|_{t=kT_s}, \end{aligned} \tag{4}$$

where $h_E(t)$ is the photodetection impulse response including all the devices from the PD to the ADC.

In Eq. (4), the effect of modulator, $h_M(t)$, is equivalent to a cascaded filter, and it can be ignored when the modulator's bandwidth is wider than the optical sampling pulse's spectral width. Therefore, the equivalent impulse response of the proposed photonic digital receiver is proportional to the product of the time-reversed sampling pulse train and the photodetection impulse response, which can be expressed as

$$\begin{aligned} h_A(t) &= h_E(t) \sum_{m=-\infty}^{+\infty} p_s(-t - mT) \\ &\propto h_E(t) \sum_{m=-\infty}^{+\infty} s(-t - mT). \end{aligned} \tag{5}$$

As shown in Fig. 2(b), when the constraint $w_p < w_E < T_s$ is satisfied, where w_E is the width of $h_E(t)$ and w_p is the width of $p_s(t)$, the window of $h_E(t)$ can be aligned to one pulse of time-reversed sampling pulse train [6,7]. In this case, the equivalent impulse response of the proposed photonic digital receiver, which is corresponding to the red solid-line pulse in Fig. 2(b), can be expressed as

$$h_A(t) \propto s(T-t). \tag{6}$$

Equation (6) indicates that the impulse response of the proposed photonic digital receiver can be directly proportional to the time-reversed temporal shape of the digital signal's waveform. Therefore, the matched filtering of the transmitted digital signal with the specific waveform is realized. The I-SNR of the filtered results is maximized to be $2E/N_0$ at the sampling points kT_s, where E and N_0 are the single waveform energy and the noise power spectral density, respectively [2]. The sampling results of the filtered signal can be directly obtained by an ADC. The binary sequence $\{a_i\}$ can be recovered through comparing the sampling results with the decision threshold. The theoretical bit error rate can be calculated as [2]

$$p_e = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E}{N_0}}\right), \tag{7}$$

where the function erfc() is the complementary error function.

It is worth noting that the transmission rate and bandwidth of the proposed receiver can reach tens of GHz since the repetition rate of the optical sampling pulse train, the bandwidth of the existing modulators, the bandwidth of the LPF, and the sampling rate of ADC can all reach this magnitude at present.

Figure 3 shows the experimental setup of the proposed photonic digital receiver. The devices in the dotted frame are employed to generate the matched optical sampling pulse train. The continuous-wave (CW) light generated by a tunable laser is launched into the first 20 GHz MZM biased at quadrature with a half-wave voltage of ~ 3.4 V. The electric pulse train, whose pulse shape is similar to the transmitted signal's specific waveform, is generated from the first channel of the arbitrary waveform generator (AWG) (Keysight, M8195A). Through modulating the CW light by the electric pulse train, we can obtain the optical sampling pulse train with the waveform similar to the transmitted signal's. The shaping of the optical sampling pulse can be easily realized through adjusting the waveform of the electric pulse train. It is worth noting that there is always a DC term in the optical sampling pulse train due to the CW light's unmodulated item, which leads to a passband at the passband location of the analog LPF [8]. It does not matter when the signal is transmitted through the bandpass transmission, and a high-pass filter is applied to avoid the low-frequency interference in the received signal. The optical sampling pulse train is then modulated by the simulated received signal generated from

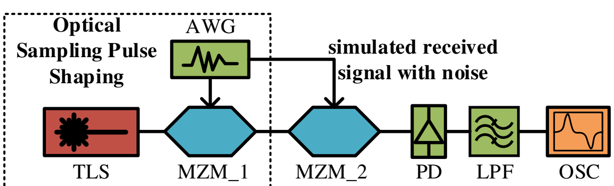

Fig. 3. Experiment setup of the proposed photonic digital receiver. TLS, tunable laser; MZM, Mach–Zehnder modulator; AWG, arbitrary waveform generator; PD, photodiode; LPF, low-pass filter; OSC, oscilloscope.

the second channel of the AWG in the second 20 GHz MZM, biased at quadrature with a half-wave voltage of ~ 4.6 V. The PD with trans-impedance amplifier and ~ 500 MHz bandwidth is used to implement the O/E conversion. Finally, the electronic pulses are filtered by the LPF with the 74 MHz bandwidth and measured by an oscilloscope (OSC) (Tektronix DSA70804). The matched filtered signal's waveform is captured by the OSC, and the sampling results can also be extracted from the measured waveform.

Figure 4 shows the specific waveform of the digital signal 1 adopted in the experiment, $s(t)$, which is the product of a Gaussian envelope with the full width at half maximum (FWHM) of 2 ns and a cosine function of 1 GHz. The waveform

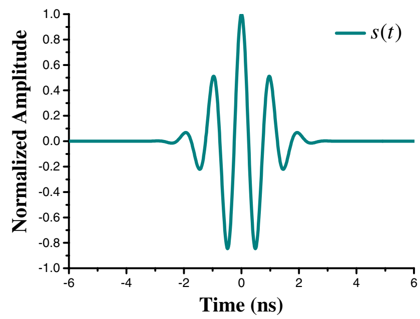

Fig. 4. Waveform of the digital signal 1, $s(t)$.

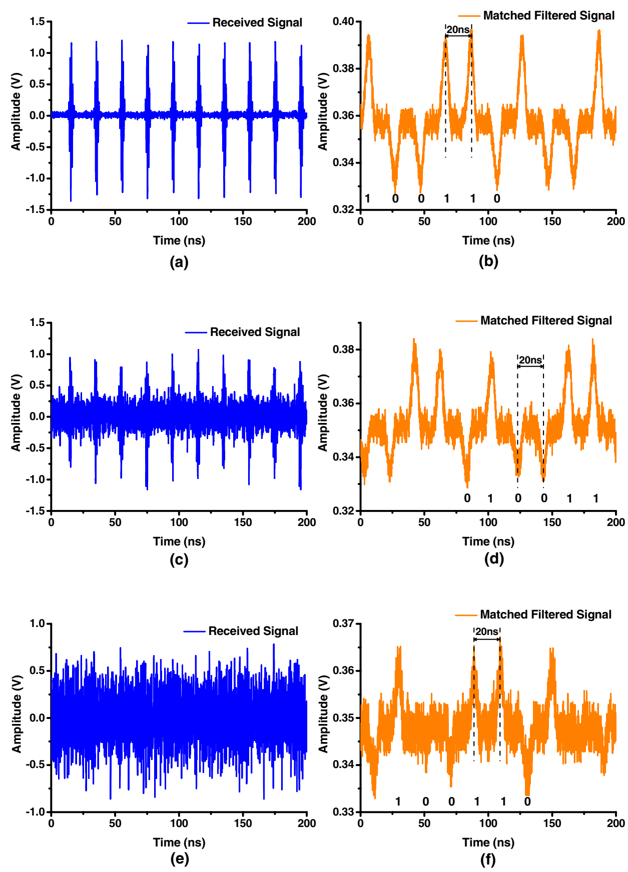

Fig. 5. Measured received signal with a different maximum I-SNR [(a) ~ 20 dB, (c) ~ 6 dB, and (e) ~ -6 dB] and the corresponding matched filtered signal [(b), (d), and (f)].

of the digital signal 0 is just reversed, $-s(t)$. The transmission rate of the digital signal and the optical sampling pulse train's repetition rate are both set as 50 MHz. The received signal is designed by combining the digital signal waveform and the white noise.

The received signal with a different maximum I-SNR is measured and shown in Figs. 5(a), 5(c), and 5(e). The maximum I-SNR is set as ~ 20 dB, ~ 6 dB, and ~ -6 dB in Figs. 5(a), 5(c), and 5(e), respectively. The digital information contained in the received signal is the loop of 100110. Comparing Figs. 5(a), 5(c), and 5(e), one can see that the signal is gradually submerged into the noise as the I-SNR decreases, and it cannot be detected and distinguished through direct sampling. Figures 5(b), 5(d), and 5(f) show the measured matched filtered signal after the LPF when the optical sampling pulse is shaped similar to $[s(t) + b]$, where b is a DC term. Since the measured 1 dB width of the photodetection response is about 2.92 ns, which basically satisfies the condition required by Eq. (6), and the shape of optical sampling pulse is matched with the specific waveform, the I-SNR of the filtered signal is maximized at the peaks and valleys. The peaks and valleys correspond to the digital signals 1 and 0, respectively. The theoretical maximized I-SNR of the filtered signal in Figs. 5(b), 5(d), and 5(f) is about 4817, 193, and 12, respectively, and the corresponding theoretical bit error rate is about ~ 0, 4.1e-44, and 0.00026, respectively. The DC term in the filtered signal is caused by the CW light's unmodulated item in both modulators, and its value is corresponding to the decision threshold. Comparing Figs. 5(b), 5(d), and 5(f), one can see that the peak or valley can be sampled at the repetition rate of 50 MHz, and the peak-to-peak value is ~ 70 mV, ~ 50 mV, and ~ 30 mV, respectively. The digital information contained in the received signal can be sampled and distinguished correctly by the proposed photonic digital receiver, even when the signal is submerged into the noise.

In conclusion, we present a photonic digital receiver that can realize the matched filtering of the digital signal and sampling. Through shaping the optical sampling pulse according to the transmitted digital signal's waveform, the I-SNR of the filtered signal can be maximized at the sampling points. The proposed photonic digital receiver is theoretically analyzed, and the received signal with a different noise power level is detected and correctly distinguished in experiments.

Funding. National Natural Science Foundation of China (61535006, 61627817).

Disclosures. The authors declare no conflicts of interest.

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