Optical Arbitrary Waveform Generation Based Optical-Label Switching Transmitter with All-Optical Label Extraction

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Abstract: This paper introduces a modulation-format transparent optical-label switching transmitter based on optical arbitrary waveform generation. Packets consisting of 100 Gb/s payloads with 40 Gb/s labels and all-optical label extraction are demonstrated.

OCIS codes: (060.4510) Fiber communications; (060.1155) All-optical networks.

1. Introduction

Optical-label switching (OLS) is an enabling technology geared towards integration of data and optical networking [1]. The immense bandwidth provided by the optical fiber and the capability to switch packets directly are a powerful combination for the next generation photonic network. Every OLS packet consists of a data payload and a label. The payloads are switched all-optically by the OLS core routers, while the label is allowed to be processed electrically through label extraction and rewriting. Based on how the labels are attached to the payloads, there are many labeling schemes. Subcarrier multiplexing facilitates relatively simple all-optical extraction and rewriting by placing encoded labels as spectral components on a subcarrier close to the baseband occupied by the data payloads [2]. The concept of label has been implemented in a number of promising technologies, including OFDM based LightLabel monitoring [3]. Modern optical networks simultaneously demand high data rates, high spectral efficiency, high capacity and low latency; however, the modulation and the spectral placement of the optical labels in the current subcarrier modulation method restrict the bandwidth of the data payload and thus constrain future upgrades. This paper pursues a new approach for OLS by employing optical arbitrary waveform generation (OAWG) [4]. Fig.1 (a) illustrates Fourier synthesis based OAWG by parallel line-by-line manipulations of an optical frequency comb (OFC) [5] [6]. This technology can create complex OLS packets in arbitrary data rates and modulation formats. Static intensity and phase modulations on each optical comb line generates identical OLS packets that repeat at the rate corresponding to the comb line frequency spacing. Infinite-length OLS packets generation is possible using time-varying intensity and phase modulations provided that the modulators have bandwidths equal to or beyond the comb spacing frequency [4]. OAWG based OLS transmitter can exploit low-speed and independent modulations of the OFC to generate optical labels and data payloads of high data rates in any format. In this paper, we experimentally demonstrate an OAWG based OLS transmitter by generating 100 ps duration repetitive OLS packets with 10-bit 100 Gb/s payloads (1011100110) and 4-bit 40 Gb/s labels (0110). The experiment also demonstrates all-optical extraction of the optical labels from the packets using a fiber Bragg grating (FBG).

2. Experimental setup

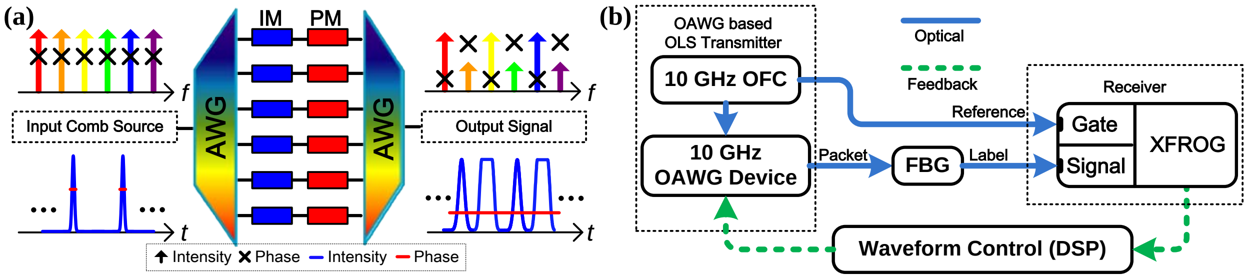

Fig. 1 (a) An arrayed-waveguide grating (AWG) pair based waveform shaper. IM: intensity modulator; PM: phase modulator. (b) Experimental arrangement for the generation and separation of optical-label switching packets with 10-bit 100 Gb/s payloads and 4-bit 40 Gb/s labels. OFC: optical frequency comb; OAWG: optical arbitrary waveform generation; XFROG: cross-correlation frequency resolved optical gating; DSP: digital signal processing. FBG: fiber Bragg grating.

Fig. 1(b) shows the experimental arrangement for packet generation, separation and all-optical label extraction and retrieval. A single-frequency laser is modulated by a dual-electrode Mach-Zehnder modulator and a phase modulator to generate an OFC with about 50 comb lines. The number of comb lines is reduced to 26 using a knife-edge filter by physically blocking the extra comb lines in the corresponding spectral domain. The spacing of the OFC is 10 GHz, therefore its time-domain representation is a repetitive pulse train with a period of 100 ps. The pulse-width is 3 ps, which indicates nearly transform-limited operation [5]. The OFC is split into two parts. One part is sent to the OAWG device, where the 26 comb lines are shaped to be packets consisting of 10-bit 100 Gb/s payloads and 4-bit 40 Gb/s labels. The other part serves as a reference pulse for cross-correlation frequency-resolved optical gating (XFROG), which is a phase sensitive measurement technique to obtain the complete intensity and phase information of the extracted label waveforms.

Inside the OAWG device, a 10-GHz spacing silica arrayed-waveguide grating (AWG) pair together with intensity and phase modulator (IM and PM) arrays acts as a waveform shaper (WS) [5]. As Fig. 1(a) indicates, the two AWGs work as a multiplexer and a demultiplexer respectively. The multiplexer assigns each comb line onto a discrete waveguide according to its frequency. Then, resistive heaters based integrated thermo-optic IMs and PMs adjust the intensity and phase of each comb line individually to exactly achieve the target intensity and phase under the instruction from the computer controlled digital signal processing (DSP). After shaping the OFC into the target spectrum, the demultiplexer combines all the spectral lines to yield the desired OLS packet waveform. More than 20 dB of intensity extinction and 2π rad of phase shift can be achieved [5].

An FBG extracts the labels from the OLS packets generated by the OAWG device. XFROG retrieves the labels, yields their full intensity and phase profile, and sends the information to the waveform control DSP [7]. The DSP compares the measured intensity and phase with target values, and adjusts intensity and phase modulator settings in an iterative fashion in order to approach the target waveform [4].

Since the OAWG device can only support a limited bandwidth, the data pulse train is first sent through a band-limited filter to ensure that the target waveform can be resolved by the OAWG based transmitter. A raised cosine pulse with a roll-off factor β of 1 is used in the experiment to minimize time domain ripple and reduce the crosstalk between adjacent bits. An additional advantage of a raised cosine pulse is its property of zero inter-symbol interference (ISI) at each impulse location in the time domain.

3. Results and discussion

The experiment utilized example cases where an OLS packet with a 10-bit 100 Gb/s payload (1011100110) and a 4-bit 40 Gb/s label (0110) are generated in NRZ and RZ OOK modulation formats [8]. Here the single-sideband subcarrier multiplexing (SSB-SCM) labeling method is implemented using a sub-carrier frequency at 130 GHz.

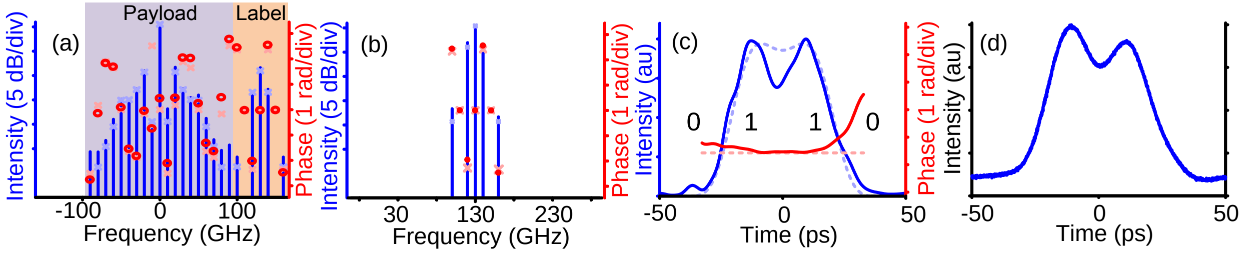

Fig. 2. Label extraction results (target intensity: blue “x” or blue dashed line, measured intensity: blue stem or blue solid line; target phase: red “x” or red dashed line; measured phase: red circle or red solid line). NRZ-OOK: (a) packet spectrum, (b) label spectrum, (c) label waveform and (d) label detected by oscilloscope.

Fig. 2 and Fig. 3 illustrate the label extraction results for NRZ and RZ OOK formats. Fig. 2(a) and Fig. 3(a) provide the spectra of the target packet and the measured packet. As shown in the figures, every OLS packet consists of a payload and a label. The payload occupies the baseband, while the label lies in the upper sideband. Fig. 2(b) and Fig. 3(b) are the target and extracted labels’ spectra showing only the 7 comb lines that represent the label after filtering by the FBG.

Fig. 2(c) and Fig. 3(c) are the corresponding time domain waveforms measured by XFROG. The small deviations between the measured and target waveforms are largely due to shaping error that comes from the OAWG device’s intensity and phase adjustments limitations. Fig. 2(d) and Fig. 3(d) shows the label waveforms detected by an oscilloscope with 50 GHz bandwidth without the additional filtering. Both label waveforms demonstrate the feasibility and effectiveness of using an FBG to extract labels from the OLS packets which are generated by an OAWG based OLS transmitter.

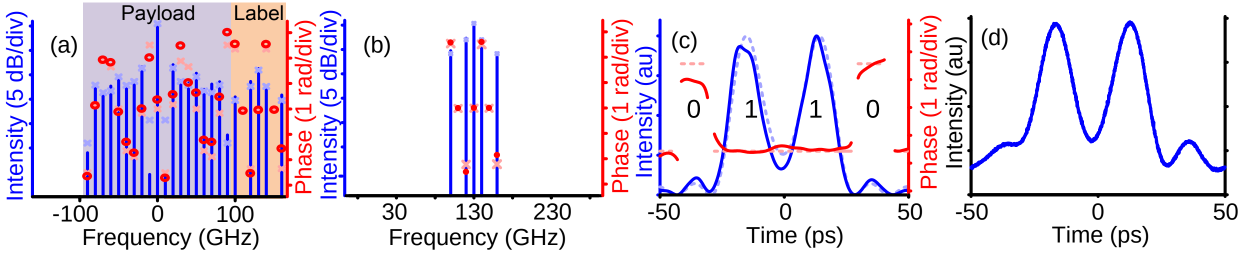

Fig. 3. Label extraction results (target intensity: blue "x" or blue dashed line, measured intensity: blue stem or blue solid line; target phase: red "x" or red dashed line; measured phase: red circle or red solid line). NRZ-OOK: (a) packet spectrum, (b) label spectrum, (c) label waveform and (d) label detected by oscilloscope.

Fig. 4 shows the eye diagrams and BER results of the extracted labels of the fixed patterns. The two BER curves are estimated from eye diagrams (shown in Fig. 4(a) and Fig. 4(b)) obtained via oscilloscope [9] plotted against average total power. The label signals in both modulation formats indicate error-free operations (BER < 10^{-10}) exploiting the all-optical label extraction from the packet signals generated by the OAWG.

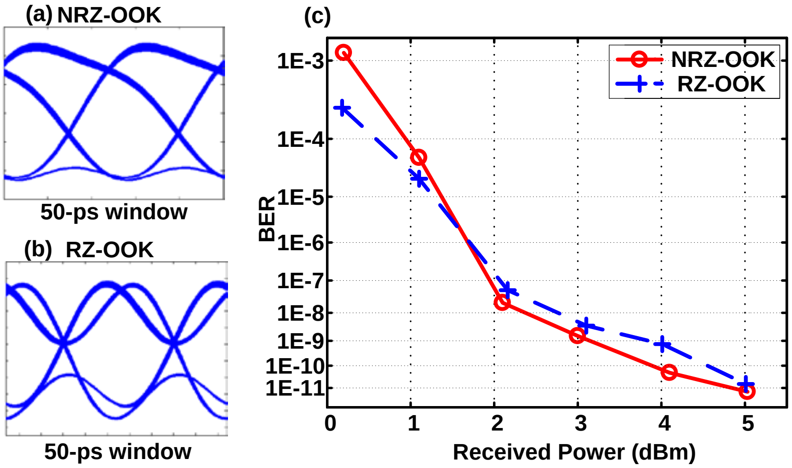

Fig. 4. Experimental measurements of (a) NRZ-OOK eye diagram, (b) RZ-OOK eye diagram, and (c) estimated BER of the extracted labels.

4. Conclusion

We have experimentally demonstrated OLS packet generation and all-optical label extraction from a highly versatile OAWG based OLS transmitter capable of supporting data and label modulation of any modulation format. Experimental results for label extraction for NRZ and RZ OOK formats indicate error-free performance.

5. References

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