Optical Arbitrary Waveform Generation-Based Packet Generation and All-Optical Separation for Optical-Label Switching

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Abstract—This letter introduces a versatile modulation-format transparent optical-label switching (OLS) transmitter based on optical arbitrary waveform generation (OAWG) and all-optical label extraction. The transmitter creates OLS packets, each with a payload and a label generated by OAWG. With the use of a circulator and a fiber Bragg grating (FBG), the payload and label are simultaneously extracted from the packet. Generation and separation of a repeated 100-ps packet with a 10-bit 100-Gb/s payload and a 4-bit 40-Gb/s label in nonreturn-to-zero and return-to-zero on-off keying formats indicate the potential for future OLS packet switching networks using an OAWG-based transmitter and an FBG to remove and add labels. Retrieved spectral and temporal waveform of both the payloads and labels show clearly spectral separation and temporal overlap.

Index Terms—Arrayed-waveguide grating (AWG), fiber Bragg grating (FBG), Fourier synthesis, label extraction, optical-label switching (OLS).

I. INTRODUCTION

The exponential growth in Internet data traffic demands scalable high-capacity networks that can handle future bandwidth needs. Optical packet switching networks support data packet forwarding at high data rates. Optical-label switching (OLS) is an enabling technology geared towards seamless integration of data networking on an all-optical platform [1] while supporting interoperability between optical packet, burst, flow, and circuit switching. OLS exploits the extensive bandwidth provided by the optical fibers and the capability of switching data directly in the optical domain. OLS can employ various advanced modulation formats and multiplexing techniques offering high spectral efficiency. A possible future Internet architecture includes the OLS technology that provides ultralow-latency and high-throughput packet forwarding at the core nodes working together with edge routers interfacing with the client networks. Fig. 1 shows the architecture of the OLS core router, which forwards the optical packets based on their label contents through all-optical switching of data payloads, all-optical label extraction and rewriting, and electronic forwarding table look-up and decision. Among numerous optical labeling schemes proposed [1], subcarrier multiplexing facilitates relatively simple all-optical extraction and rewriting by placing encoded labels as spectral components [2]. As modern optical networks demand higher throughput, a new labeling scheme is necessary to overcome the limitation of the current subcarrier modulation method where the modulation and the spectral placement of the optical labels restrict the bandwidth of the data payload and the prospects of future upgrades.

Recent progress in optical arbitrary waveform generation (OAWG) [3] has indicated its capability of creating arbitrary waveforms through the line-by-line intensity and phase modulations of each individual spectral line across the entire bandwidth of a coherent optical frequency comb (OFC) [4]. The OAWG methodology is a modulation format independent technique that can offer solutions for applications that require full control of a signal with tremendous bandwidth. The maximum data rate of OLS packets is determined by the total spectral bandwidth of the OFC and the modulation format used. The proposed OAWG-based OLS transmitter exploits low-speed (terahertz) and independent parallel modulations of the OFC spectral lines to independently generate optical packets with labels and high-speed (terahertz) data payloads in any modulation format. In this letter, the proof-of-principle demonstration uses dc modulations for high-bandwidth repetitive packet generation and separation.

II. THEORY

Fig. 2 illustrates Fourier synthesis-based OAWG by parallel line-by-line manipulations of an OFC. The static intensity and phase modulations on each optical comb line generate identical OLS packets that repeat at a rate corresponding to the

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comb line frequency spacing. Generation of OLS packets much longer than an OFC period is possible using time-varying intensity and phase modulations, provided that the modulators have bandwidths equal to or beyond the comb spacing frequency. Inside the OAWG device, a pair of 10-GHz spacing silica arrayed-waveguide gratings (AWGs), together with 64 channels of intensity and phase modulators (IMs and PMs), act as the waveform shaper (WS) [4]. The two AWGs serve as a demultiplexer and multiplexer, respectively. The demultiplexer assigns each comb line onto a discrete output waveguide according to its frequency. Then, integrated thermo-optic IMs and PMs based on resistive heaters adjust the intensity and phase of each comb line individually to achieve the target intensity and phase, as specified by the computer controlled digital signal processing (DSP). After shaping the OFC into the target spectrum, the multiplexer combines all of the spectral lines to yield the desired OLS packet waveform.

In this experiment, the payload and label of the OLS packet created by OAWG occupy 19 and 7 comb lines, respectively. In the spectral domain, the payload can be expressed as follows:

\[ P(\omega) = \sum_{k=-9}^{k=+9} A_k \delta[\omega - (\omega_0 + k\Omega)] \]

and the label is

\[ L(\omega) = \sum_{k=-3}^{k=+3} B_k \delta[\omega - (\omega_0 - \omega_{sc} + k\Omega)]. \]

In the above two equations, \( A_k \) and \( B_k \) are the corresponding complex amplitudes of each frequency component of the payload and label, respectively. \( \omega_0 \) represents the optical signal frequency, \( \omega_{sc} \) is the subcarrier frequency, and \( \Omega \) is the comb line spacing. The OLS packet energy spectrum is the sum of the payload and label energy spectra.

The FBG reflection has a flat-top response with 1-, 3-, and 30-dB bandwidths of 176, 191, and 249 GHz centered around the payload center frequency to reflect only the payload signal. The FBG transmission is approximately the inverse of the reflection, thus isolating the label.

In this letter, the experiment utilizes example cases in which a repetitive OLS packet with a 10-bit 100-Gb/s payload (0110010110) and a 4-bit 40-Gb/s label (0110) are generated in nonreturn-to-zero (NRZ) and return-to-zero (RZ) on–off keying (OOK) modulation formats [5]. The single-sideband subcarrier multiplexing (SSB-SCM) labeling method is implemented using a subcarrier frequency of 130 GHz.

Fig. 3 shows the experimental arrangement for packet generation and separation. Modulations of a single-frequency laser by a dual-electrode Mach–Zehnder modulator and a PM generate an OFC with about 50 comb lines. The number of comb lines is reduced to 26 by using a knife-edge filter which physically blocks the extra comb lines in the corresponding spectral domain. In this experiment, the OFC’s spacing is 10 GHz, and its time-domain representation is a repetitive pulse train with a period of 100 ps. The pulsewidth is ~2 ps, which indicates nearly transform-limited operation [4]. The OFC is power-split into two, and one part is sent to the OAWG device, where the 26 comb lines are shaped using only dc thermo-optic modulations into a particular OLS packet which repeats every 100 ps and consists of a 10-bit 100-Gb/s payload and a 4-bit 40-Gb/s label. The modulators in the OAWG device achieve more than 20-dB intensity extinction and 2\pi rad of phase shift when electrical currents corresponding to 450 and 650 mW flow through the respective heaters. The generated OLS packets are sent to a circulator, and to an FBG. The center frequency and the bandwidth of the FBG is carefully chosen so that the FBG reflects the payloads while transmitting the labels. The payloads or labels are sent to cross-correlation frequency-resolved optical gating (XFROG) [6] for retrieval (~5-dBm input power). XFROG is an inherently averaged, phase-sensitive measurement technique which measures the full intensity and phase profile of an unknown waveform using a precharacterized reference waveform (the other half of the OFC) which is used for feedback in the waveform control DSP [7].

To obtain accurately shaped waveforms, the DSP compares the measured waveforms’ intensity and phase with the target values and adjusts the IM and PM settings to approach the target waveform. In this experiment, typically six iterations are needed to obtain a close match between the measured and target waveforms and compensate for optical and thermal crosstalk inside the OAWG device. In a real system, accurate device calibration needs to be performed regularly to avoid the slow iterative process. Fig. 4 shows the target and measured OLS packet spectra. For both NRZ-OOK and RZ-OOK OLS packets, the payload occupies the baseband, while the label lies in the lower sideband.

Figs. 5 and 6 illustrate the payload and label separation results for the NRZ-OOK and RZ-OOK formats. Figs. 5(a) and 6(a) compare the spectra of the target payload with the extracted payload, and Figs. 5(b) and 6(b) show the corresponding time domain waveforms measured by XFROG. Additional offline rectangular filtering (in software) eliminates the out-of-band noise.
Similarly, Figs. 5(c),(d) and 6(c),(d) show the spectra and temporal waveforms for the extracted label. The small deviations between the measured and target waveforms are largely due to shaping and measurement errors, which are primarily due to the optical crosstalk from adjacent comb lines and the thermal crosstalk from the resistive heaters. Fig. 7 shows the eye diagrams of the extracted payloads and labels. NRZ-OOK: (a) payload and (b) label; RZ-OOK: (c) payload and (d) label. The possibility that the 40-Gb/s label and the 100-Gb/s payload can be detected using a receiver with sufficient bandwidth.

IV. CONCLUSION

We have proposed and realized a highly versatile and modulation format independent OAWG-based OLS transmitter capable of supporting OLS packets generation and all-optical payload and label separation. These results indicate the potential for OAWG-based OLS in the next-generation all-optical packet switching networks. We have demonstrated OAWG based on dc thermo-optic modulations as a proof-of-principle. When the InP-based OAWG with fast (>GHz) electrooptic modulations become available [9], dynamic generation of the OLS packets with extended lengths and dynamically varying bit patterns will be possible.

REFERENCES