Applications of optical duobinary in optical carrier suppression and separation labeling

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Received January 13, 2010

A novel approach is used to implement optical carrier suppression and separation (OCSS) labeling. Then, the performance of 10/40-Gb/s duobinary payload with 2.5-Gb/s amplitude shift keying (ASK) or duobinary label by numerical simulations is studied. Influencing factors, such as demultiplexer bandwidth and fiber Bragg grating (FBG) filter bandwidth, are investigated. Simulation result shows that the received sensitivity of ASK label is higher than that of the duobinary label, while the received sensitivity of duobinary payload with duobinary label is higher than that with ASK label.

OCIS codes: 060.2330, 060.4080.

doi: 10.3788/COL20100807.0642.

All-optical label switching is a promising approach in switching and routing packets in optical layers for next-generation optical packet switching networks[1−5]. In optical labeling, the optical carrier suppression and separation (OCSS) technique has been proposed as a prevailing approach due to several reasons: 1) absence of extinction ratio (ER) limitation for generating payload or label; 2) narrow bandwidth for transporting both label and payload, thus allowing better spectral efficiency; 3) easy separation of payload and label by filtering. However, we have noticed that the OCSS schemes previously reported mostly used differential phase-shift-keying (DPSK)[6−8] or differential quadrature phase-shift-keying (DQPSK)[9] modulated payload. The typical DPSK receiver structure is based on interferometric-detection where one-bit period Mach-Zehnder delay line interferometer (DLI) is difficult to fabricate and needs very tight temperature control in order to provide exactly one-bit period delay. Thus, the transmission cost and system difficulty increase for DPSK modulation. For DQPSK and some other advanced modulation formats, the receivers are more complicated. Therefore, cost-effective solutions for OCSS implementation are highly desirable. Considerable effort has been devoted on the study of possible replacements[10].

Optical duobinary format is considered attractive because of its low spectral occupancy and high tolerance to residual chromatic dispersion[11−13]. More importantly, it can utilize simple and cost-effective direct detection (DD) receivers, similar to that in on-off keying (OOK) transmission. These make it one of the most promising solutions for upgrading existing 10-Gb/s wavelength division multiplexing (WDM) systems, i.e., through simple replacement of a 10-Gb/s channel with a 40-Gb/s one without changing the design of the transmitter, receiver, or the transmission line. However, to our knowledge, applications of duobinary in OCSS system for either payload or label have not been conducted. In this letter, a novel approach for OCSS labeling is proposed. In addition, the performance of duobinary modulated payload with amplitude shift keying (ASK) or duobinary label is studied using numerical simulations. The duobinary payload is 10 or 40 Gb/s, while both ASK and duobinary labels are 2.5 Gb/s. Influencing factors like demultiplexer bandwidth and the fiber Bragg grating (FBG) filter bandwidth are investigated. Results show that for 10-Gb/s payload, the impact of FBG filter is negligible, but it is significant for 40-Gb/s payload.

The proposed system using optical duobinary for OCSS labeling is shown in Fig. 1. Operating principle of the optical carrier suppression is described as follows. The carrier frequency of the continuous wave (CW) laser was set to 193.1 THz and the laser output was injected to a dual-drive $LiNbO_3$ Mach-Zehnder modulator (MZM1). The two parameters of MZM1, which are required for π phase difference, namely $V_{\pi DC}$ (direct current (DC) voltage at both split electrodes) and $V_{\pi RF}$ (radio frequency (RF) voltage at both split electrodes), were both set to 5.0 V. Compared with the conventional method in implementing OCSS to drive the upper and lower arms of MZM1 using a pair of complementary RF sinusoidal clock signals, as shown in Ref. [8], both upper and lower arms of MZM1 in this letter were driven by the same 20-GHz RF sinusoidal clock signal. The amplitude was set to 1.25 V ($V_{\pi RF}/4$). Both upper and lower arms of MZM1 were biased by the same DC source at the minimal intensity point by setting both upper and lower bias voltages to 2.5 V ($V_{\pi DC}/2$). CW light was separated into two longitudinal modes with a fixed frequency spacing equal to twice the clock frequency (Fig. 2(b)). By varying RF sinusoidal frequency to 10 and 30 GHz, the spacing between the two longitudinal modes changed to 20 (Fig. 2(a)) and 60 GHz (Fig. 2(c)), respectively.

After carrier suppression, a demultiplexer (DEMUX) was employed to separate the two longitudinal modes. We used a single-arm MZM2 to modulate the lower

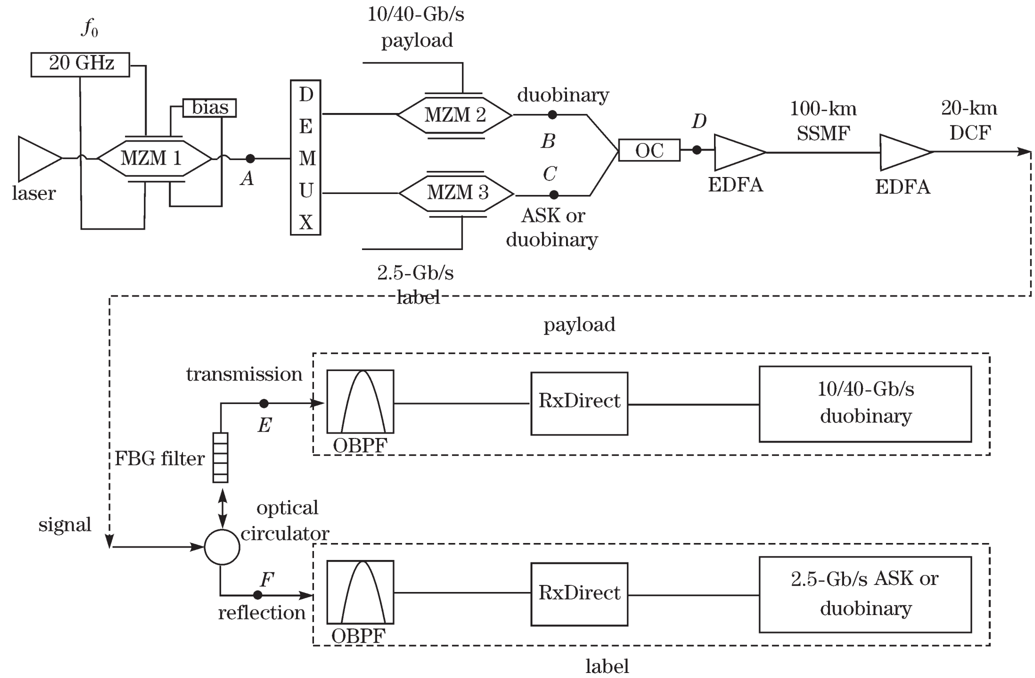

Fig. 1. Proposed OCSS scheme with the duobinary format.

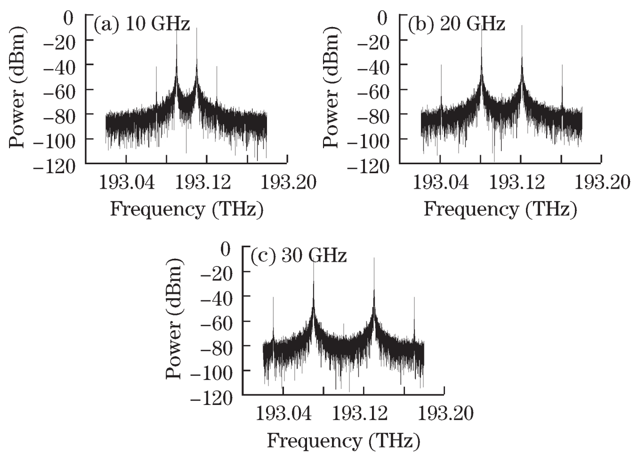

Fig. 2. Spectra of generated carrier suppressed signal.

separated frequency for 10/40-Gb/s duobinary payload and used MZM3 to modulate the upper frequency for 2.5-Gb/s ASK or duobinary label. Then, a 3-dB optical coupler (OC) was used to combine the payload and label.

The combined signal was amplified by an erbium-doped fiber amplifier (EDFA) before the 100-km standard single mode fiber (SSMF) transmission. Another EDFA was used before the 20-km dispersion compensation fiber (DCF). Dispersion values of the SSMF and the DCF were 16 and −80 ps/(nm·km), respectively, and the attenuation values of SSMF and DCF were 0.2 and 0.6 dB/km, respectively.

At the receiver, one FBG and one optical circulator were used to separate label from payload. The label signal was reflected by the FBG, and the packet payload passed through it. The extracted label and payload both went through an optical band-pass filter (OBPF) to suppress the amplified spontaneous emission (ASE) noise before the direct detection by the PIN receivers.

The duobinary transmitter setup in our scheme is shown in Fig. 3. It consisted of a duobinary precoder, a low-pass filter (LPF), and a single-arm MZM[14]. The duobinary precoder was composed of an inverter (NOT) and an AND-gate connected to a toggle flip flop (T-FF). After precoding, electrical duobinary was achieved by using an electrical fifth-order Bessel LPF with cut-off frequency at 25% of the bit-rate. The single-arm MZM with internal push-pull configuration provided the same amplitude and phase modulation capabilities as a dual-arm MZM.

The optical spectra in the system at different points (A–F in Fig. 1) are shown in Fig. 4. Point A is already presented in Fig. 2. At B and C, the duobinary or ASK modulated signals are shown in Fig. 4(a). Combined payload and label before transmission at D is shown in Fig. 4(b). The transmission and reflection components of the FBG outputs at E and F are displayed in Fig. 4(c). In Fig. 4, the bandwidth of 2.5-Gb/s duobinary signal is much smaller than that of the 2.5-Gb/s ASK.

Figure 5 presents the effect of DEMUX bandwidth on payload and label. For the 10-Gb/s duobinary payload system in Figs. 5(a) and (c), the performances of both payloads were stable when the DEMUX bandwidth was under 30 GHz. The performance of the ASK label was likewise stable up to 25 GHz. The duobinary label

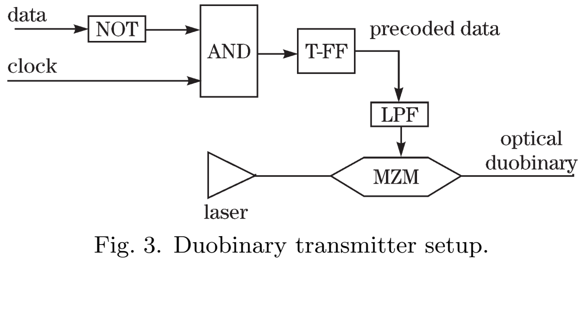

Fig. 3. Duobinary transmitter setup.

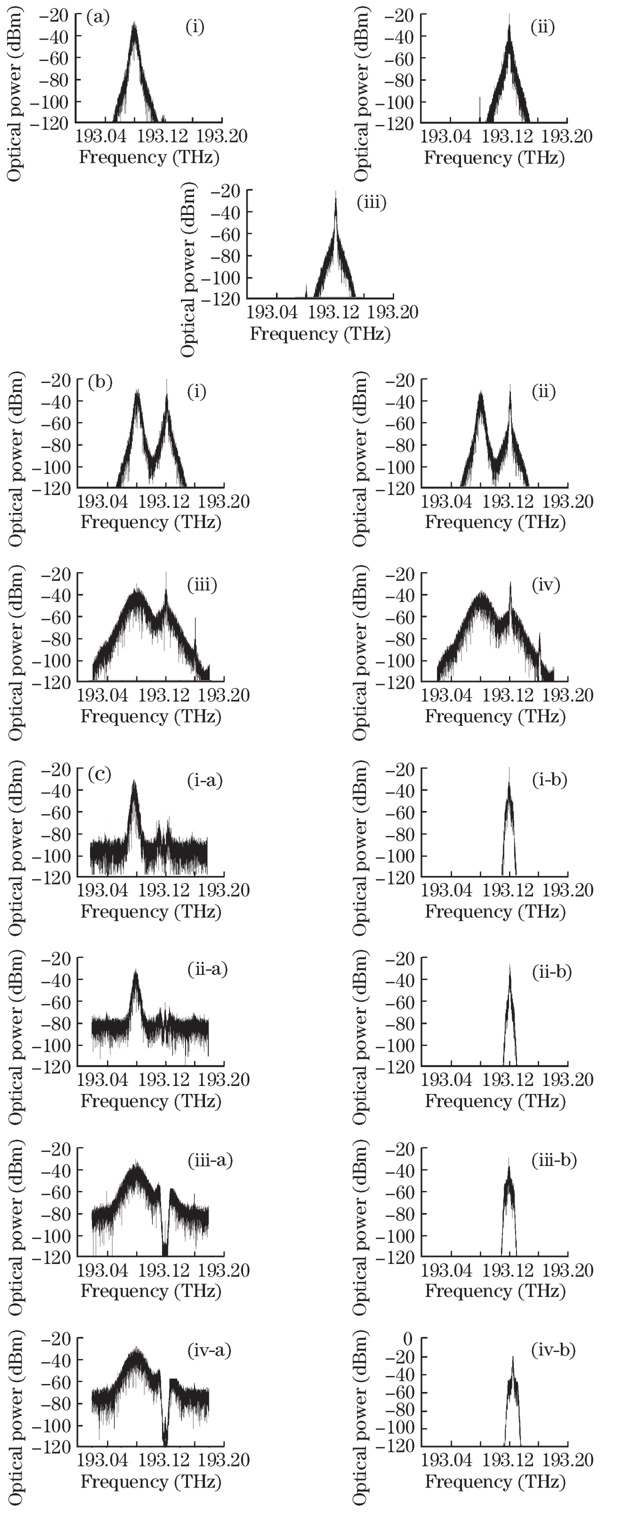

Fig. 4. Optical spectra of the system. (a) Duobinary or ASK modulation after carrier separation: (i) 10-Gb/s duobinary, (ii) 2.5-Gb/s ASK, (iii) 2.5-Gb/s duobinary; (b) combined payload and label before transmission: (i) 10-Gb/s duobinary and 2.5-Gb/s ASK, (ii) 10-Gb/s duobinary and 2.5-Gb/s duobinary, (iii) 40-Gb/s duobinary and 2.5-Gb/s ASK, (iv) 40-Gb/s duobinary and 2.5-Gb/s duobinary; (c) spectra of separated payload and label after FBG filter: (i-a) 10-Gb/s duobinary and (i-b) 2.5-Gb/s ASK, (ii-a) 10-Gb/s duobinary and (ii-b) 2.5-Gb/s duobinary, (iii-a) 40-Gb/s duobinary and (iii-b) 2.5-Gb/s ASK, (iv-a) 40-Gb/s duobinary and (iv-b) 2.5-Gb/s duobinary.

performance was stable up to 35 GHz. The performances were degraded at 40 GHz and degraded to 45 GHz level. The ASK label degraded faster than the duobinary label. For the 40-Gb/s duobinary payload system, the payload bit-error rate (BER) displayed the best performance at 35 GHz, while the 2.5-Gb/s ASK or duobinary label performed similarly with the 10-Gb/s system, as shown in Figs. 5(b) and (d)

The impact of FBG filter bandwidth on payload and extracted label is shown in Fig. 6. For the 10-Gb/s duobinary payload system, the performance of payload was unchanged when FBG bandwidth varied from 5 to 45 GHz (Figs. 6(a) and (c)). The ASK signal exhibited the best performance at 20 GHz and slightly degraded from 20 to 45 GHz. On the other hand, the duobinary label maintained a stable performance from 15 to 45 GHz. For the 40-Gb/s duobinary payload system, Figs. 6(b) and (d) show that 20 GHz is possibly the best bandwidth for the system with the ASK label where the best performance for both label and payload resulted. The duobinary payload with duobinary label

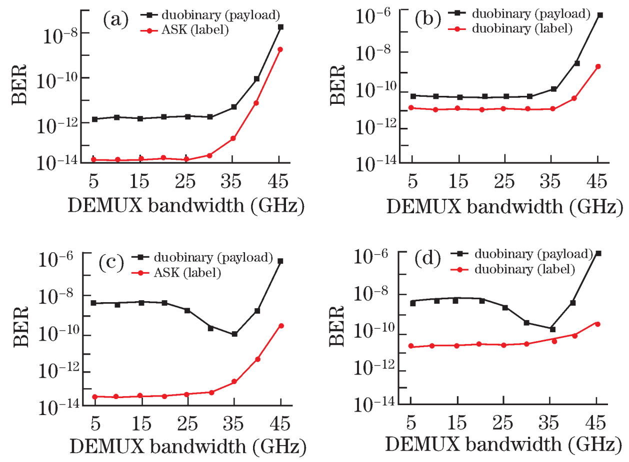

Fig. 5. Effect of DEMUX bandwidth on the BER of payload and label. 2.5-Gb/s ASK label with (a) 10-Gb/s and (b) 40-Gb/s duobinary payloads, 2.5-Gb/s duobinary label with (c) 10-Gb/s and (d) 40-Gb/s duobinary payloads.

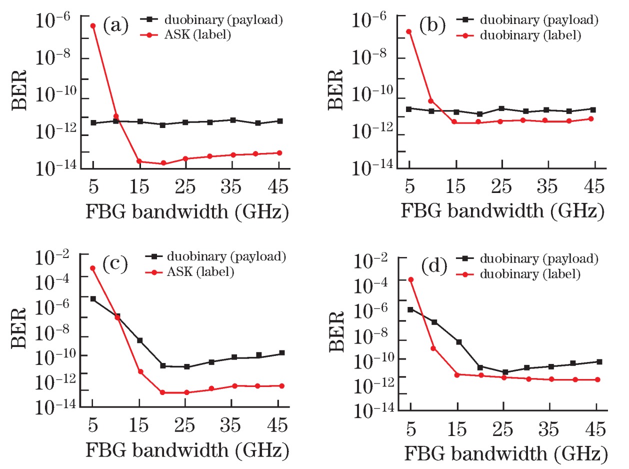

Fig. 6. Impact of FBG filter bandwidth on BER. 2.5-Gb/s ASK label with (a) 10-Gb/s and (b) 40-Gb/s duobinary payloads, 2.5-Gb/s duobinary label with (c) 10-Gb/s and (d) 40-Gb/s duobinary payloads.

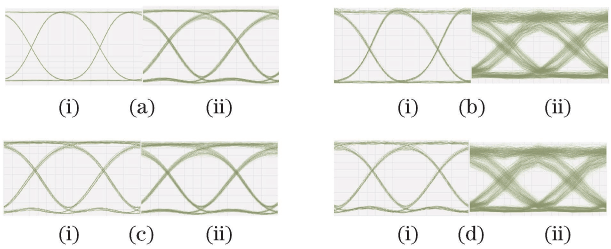

Fig. 7. Measured eye diagrams of payload and label. (a) (i) 2.5-Gb/s ASK label and (ii) 10-Gb/s duobinary payload, (b) (i) 2.5-Gb/s ASK label and (ii) 40-Gb/s duobinary payload, (c) (i) 2.5-Gb/s duobinary label and (ii) 10-Gb/s duobinary payload, and (d) (i) 2.5-Gb/s duobinary label and (ii) 40-Gb/s duobinary payload.

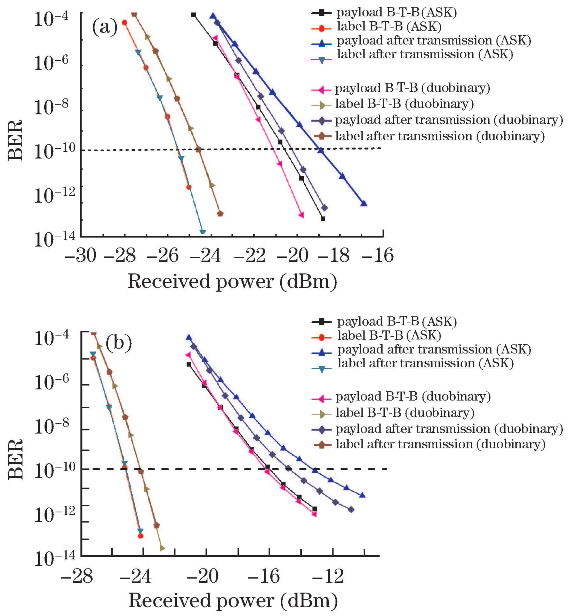

Fig. 8. BER versus received optical power of the payload and label. (a) 10-Gb/s and (b) 40-Gb/s duobinary payloads with 2.5-Gb/s ASK or duobinary label.

obtained the best performance at 25 GHz while the duobinary label exhibited almost the same performance from 25 to 45 GHz.

In Fig. 7, the measured eye diagrams of the duobinary labels are almost the same when the payload varies from 10 to 40 Gb/s. Likewise, the ASK eye diagram with 40 Gb/s payload deteriorates more than the 10-Gb/s payload. This indicates that the crosstalk between the duobinary payload and ASK label is higher than that between duobinary payload and duobinary label. The main reason is the narrower spectrum bandwidth of the duobinary signal compared with the ASK.

The BER performance of the payload and label against the received power is shown in Fig. 8. No power penalty was observed for the label after transmission in both 10- and 40-Gb/s systems. The receiver sensitivities for the ASK label were −25.55 and −25.08 dBm in the 10- and 40-Gb/s systems, respectively. The receiver sensitivities for the duobinary label were −24.58 and −24.20 dBm in the 10- and 40-Gb/s systems, respectively. The back-to-back (B-T-B) receiver sensitivity of the 10-Gb/s payload with duobinary label was −21.12 dBm, which was 0.5 dBm higher than that of the payload with the ASK label. After transmission, the receiver sensitivity of 10-Gb/s payload with duobinary label was −20.25 dBm, which was 1.28 dBm higher than that of the payload with the ASK label. For the 40-Gb/s system, the B-T-B receiver sensitivity of the payload with duobinary label was −16.25 dBm; this was almost the same as that of the payload with the ASK label. After transmission, the receiver sensitivity of payload with duobinary label was −14.72 dBm, which was 1.48 dBm higher than the payload with the ASK label.

In conclusion, we use the same RF sinusoidal clock signal to implement OCSS, and study the performance of 10/40-Gb/s duobinary payload with 2.5-Gb/s ASK and duobinary label as applied in the OCSS system. The DEMUX and FBG filter bandwidths display different impacts on the system, which are negligible at 10 Gb/s but significant at 40 Gb/s. This shows that the received sensitivity for the ASK label is higher than the duobinary label, while the received sensitivity for duobinary payload with duobinary label is higher than the payload with the ASK label. To combine OCSS labeling with optical duobinary modulation, our scheme exhibits the advantages of compact architecture, low cost, easy control, and low crosstalk between the payload and label. All these characteristics make the scheme more applicable in practical networks.

This work was supported by the National “973” Project of China (No. 2010CB328300), the National Natural Science Foundation of China (Nos. 60677004, 60977046, and 60702049) the National “863” Project of China (No. 2009AA01Z220), the Teaching and Scientific Research Foundation for the Returned Overseas Chinese Scholars (Ministry of Education of China), and the Program for New Century Excellent Talents in University of China (No. NECT-07-0111).

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