A Hybrid OTDM Scheme With Enhanced Demultiplexing Performance

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***Abstract*—We propose a novel hybrid optical time-division multiplexing (OTDM) approach, which contains hybrid modulation formats of return-to-zero on–off keying and return-to-zero differential-phase-shift keying, and investigate its demultiplexing performance. Compared with conventional OTDM with homogenous modulation format, the target demutiplexed channel in a hybrid OTDM signal suffers from much less degradation due to the possible crosstalk from the adjacent channels. We experimentally demonstrate 84.88- to 10.61-Gb/s hybrid OTDM demultiplexing and achieve a relatively wide switching window, which cannot be realized by using the conventional OTDM. Moreover, experimental results at 42.44 Gb/s show a much larger tolerance against timing misalignment in demultiplexing, which further validates the improved demultiplexing performance by using the hybrid OTDM scheme.**

***Index Terms*—Demultiplexing, differential-phase-shift keying (DPSK), electro-absorption modulator (EAM), on–off keying (OOK), optical time-division multiplexing (OTDM).**

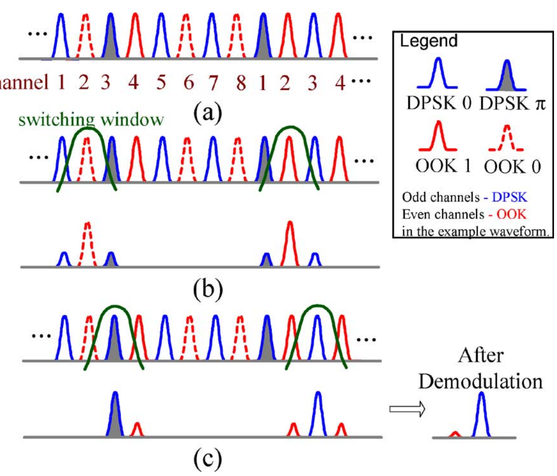

Fig. 1. (a) Signal format of our proposed hybrid OTDM approach. (b) Demultiplexing of OOK channel. (c) Demultiplexing of DPSK channel.

I. Introduction

With the ever-increasing demand in communication bandwidth, optical time-division multiplexing (OTDM) is an effective approach to upgrade the capacity of each wavelength channel in current optical systems [1]–[6]. At the receiver side, an aggregated high-speed OTDM signal is time demultiplexed to the base channel rate before detection. OTDM demultiplexing can be realized by using an electro-absorption modulator (EAM) driven by the recovered base-rate electrical clock. Compared with other demultiplexing approaches based on optical nonlinear effects [1], the EAM-based one has the merits of simpler configuration and better controllability.

However, an EAM-based demultiplexer has a relatively wide switching window, which may cause adjacent-channel crosstalk and limit its demultipelxing performance. Generally, a 160-Gb/s (or 40-Gb/s) OTDM signal could be easily demultiplexed to its base rate 40 Gb/s (or 10 Gb/s) [2], [3]. To realize higher ratio 8:1 or 16:1 demultiplexing, some sophisticated measure should be taken into account [4], [5], which requires either two sets of clock signals plus radio-frequency (RF) amplifiers or an expensive high-power RF amplifier with applied voltage exceeding the normal operation range of general commercial EAMs. In addition, the demultiplexer requires a complex and costly timing control circuit to guarantee the performance.

In this letter, we propose an OTDM scheme with hybrid return-to-zero (RZ) on–off keying (OOK) channel and RZ differential phase-shift-keying (DPSK) channel signals. With these two different modulation formats, the performance degradation induced by crosstalk from adjacent channels in a hybrid OTDM is much less than that in a conventional OTDM signal with homogeneous modulation formats [6]. Therefore, the demultiplexing performance can be greatly enhanced and the requirement on the control circuit can be relaxed. By employing an EAM operated in normal conditions, we experimentally demonstrate 84.88- to 10.61-Gb/s OTDM demultiplexing. An experimental study of a 42.44-Gb/s hybrid OTDM signal also shows that the proposed scheme offers greatly enhanced tolerance against timing misalignment in demultiplexing.

II. Principle of Operation

Fig. 1 depicts the frame format and the 8:1 demultiplexing of a high-speed hybrid OTDM signal. In a conventional OTDM signal, all channels employ either RZ-OOK or RZ-DPSK formats. However, in our proposed hybrid OTDM scheme, every even channel is in RZ-OOK format while every odd channel is in RZ-DPSK format, as illustrated in Fig. 1(a). In other words, the RZ-OOK channels are time-interleaved with the RZ-DPSK channels. Fig. 1(b) shows the 8:1 demultiplexing of an RZ-OOK channel in which the switching window covers not only the

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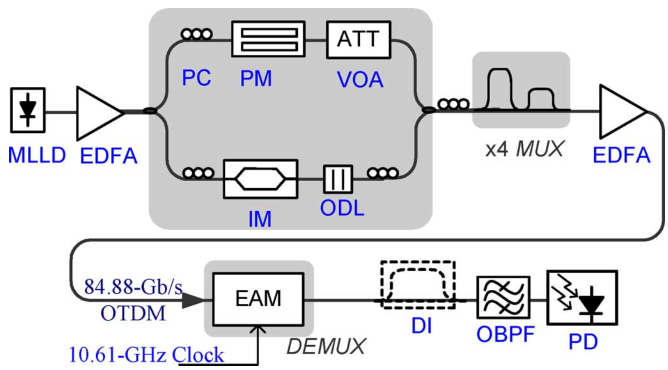

Fig. 2. Experimental setup. MLLD is mode-locked laser diode; EDFA is Erbium-doped fiber amplifier; PC is polarization controller; PM is phase modulator; VOA is variable optical attenuator; IM is intensity modulator; ODL is optical delay line; EAM is electro-absorption modulator; DI is delayed interferometer; OBPF is optical bandpass filter; and PD is photodetector.

target demultiplexed channel but also part of its two adjacent channels. In a conventional OOK OTDM signal in which all channels are in RZ-OOK formats, such demultiplexing would induce severe crosstalk from adjacent channels and may severely deteriorate the target demultiplexed channel. However, for an OOK channel in our proposed hybrid OTDM signal, the crosstalk from adjacent channels is part of the adjacent DPSK bits, having the same amount of power for either DPSK “0” or “1”. This is equivalent to adding a small amount of constant power into the target OOK channel, which may alter the detection threshold but will not induce erroneous detection due to crosstalk from adjacent channels.

Similarly, for a DPSK channel in a hybrid OTDM signal, the demultiplexing will gate part of the adjacent OOK bits. However, after DPSK demodulation, the gated part of the OOK bit will destructively interfere with that of its previous bit. That is, the gated power of the OOK bit will disappear or become as little as a quarter of its original power, depending on whether its two consecutive bits are the same or not. Therefore, the DPSK channel demodulation process can greatly alleviate the crosstalk from the adjacent OOK channels, as compared with the demultiplexing of a conventional RZ-DPSK OTDM signal.

III. Performance Improvement in 84.88-Gb/s Hybrid OTDM Demultiplexing

We have conducted an 84.88- to 10.61-Gb/s demultiplexing experiment using the hybrid OTDM scheme. Fig. 2 shows the experimental setup. A semiconductor mode-locked laser diode (MLLD)-generated 10.61-GHz pulse train (1.5-ps full-width at half-maximum (FWHM) peak-to-floor extinction ratio $>$20 dB) was first separated into two branches. Then, the two pulse trains were respectively phase modulated and intensity modulated by 10.61-Gb/s decorrelated $2^{31}-1$ data patterns. The RZ-OOK signal was adjusted by a tunable optical delay line (ODL) to have a delay of 11.8 (or 94.3/8) ps, relative to the RZ-DPSK signal. A polarization controller and a variable optical attenuator (VOA) were used to assure the two branches having the same peak power and polarization. Then, the interleaved RZ-OOK/DPSK signal was 1:4 time-multiplexed to form an 84.88-Gb/s hybrid OTDM signal as shown in Fig. 3(a).

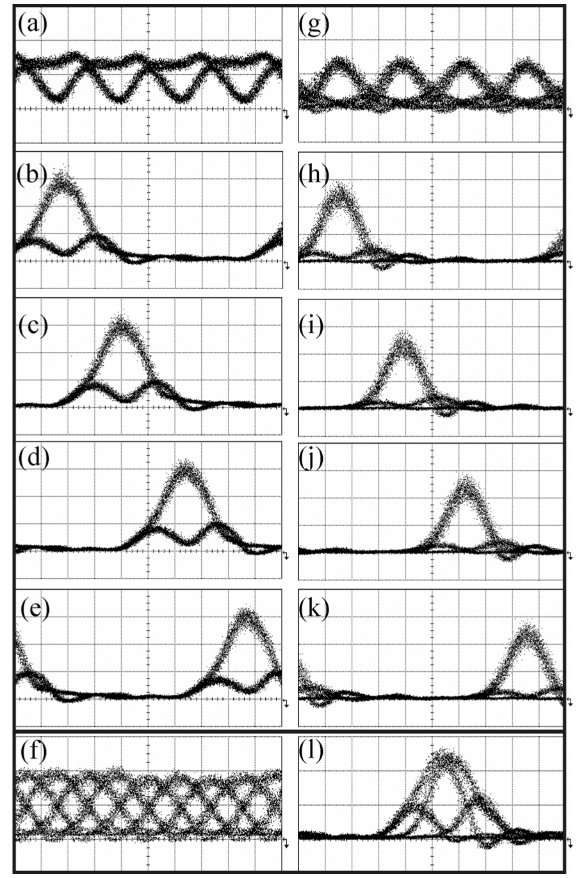

Fig. 3. Eye diagrams of (a) 84.88-Gb/s hybrid OTDM signal, (g) after DI, (b)–(e) four demultiplexed OOK channels, (h)–(k) four demultiplexed and demodulated DPSK channels, (f) 84.88-Gb/s conventional OOK OTDM signal, (l) and one of its demultiplexed channels, all detected with 50-GHz photodiode. Time scale is 10 ps/div.

After proper amplification, it was fed into a commercial EAM, driven by a 10.61-GHz clock signal for demultiplexing. The bias voltage for the EAM was -3.2 V and the RF peak-to-peak voltage was 6 V. The switching window of the EAM was measured to be around 15 ps (FWHM), which was wider than the bit period of the OTDM signal (11.8 ps). The demultiplexed RZ-OOK channels were directly detected while the RZ-DPSK channels were first demodulated via a delay interferometer (DI) with a relative delay of 94.3 ps before single-ended detection.

Fig. 3(b)–(e) shows the four demultiplexed OOK channels from the 84.88-Gb/s hybrid OTDM signal. We could observe the crosstalk from the adjacent DPSK channels but the eye is clearly open. As a comparison, Fig. 3(l) shows a demultiplexed OOK channel from an 84.88-Gb/s conventional OTDM signal [Fig. 3(f)], in which the crosstalk from adjacent channels severely distorted the eye and consequently degraded data detection. A similar distorted eye diagram was observed in the case of demultiplexing in a conventional DPSK OTDM signal, after DI demodulation. On the contrary, using our proposed hybrid OTDM, the eye diagrams of the demultiplexed and demodulated DPSK channels from our proposed hybrid OTDM were clearly open, as shown in Fig. 3(h)–(k). Again, we could see the greatly enhanced tolerance to the adjacent crosstalk by employing hybrid OTDM signals.

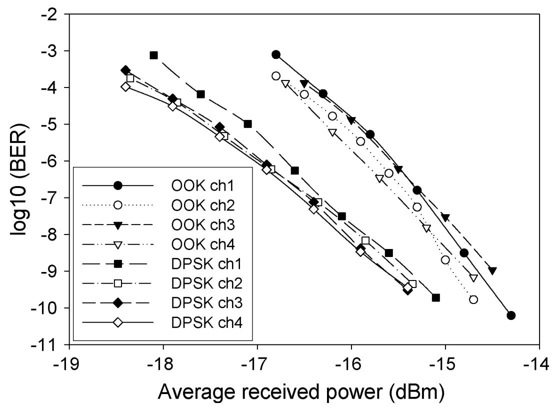

Fig. 4. BER measurements of four OOK and four DPSK channels demultiplexed from 84.88-Gb/s hybrid OTDM signal.

We have measured the bit-error rates (BER) of the eight 10.61-Gb/s demultiplexed channels from the hybrid OTDM signal, as shown in Fig. 4. Although they had around a 4-dB penalty due to the wide switching window of the demultiplexer, compared with a 10.61-Gb/s back-to-back signal, all channels could achieve error-free detection (BER $< 10^{-9}$). Comparatively, we also attempted to measure the demultiplexing performance of conventional OOK or DPSK OTDM signals, using the EAM with the same operation condition. However, synchronization loss occurred and BER could not be measured. This showed that hybrid OTDM can greatly enhance the demultiplexing performance against the adjacent-channel crosstalk. In Fig. 4, DPSK channels showed a little better receiver sensitivity than OOK channels, which agreed with the eye diagram performance as shown in Fig. 3.

IV. Enhanced Tolerance to Timing Misalignment in 42.44-Gb/s Hybrid OTDM Demultiplexing

Hybrid OTDM also showed improved performance in 42.44-Gb/s demultiplexing, as compared with conventional OTDM. Although their demultiplexing had almost the same performance under accurate timing control of the clock signal, the hybrid OTDM scheme can greatly enhance the tolerance against timing misalignment between the OTDM signal and the control clock. The experimental configuration and parameters were the same as in the above experiment, except for a 1:4 multiplexed 42.44-Gb/s OTDM signal generated. We altered the electrical delay line of the 10.61-GHz driving clock signal for the EAM.

Fig. 5 depicts the measurements of the 42.44-Gb/s demultiplexing performance under the condition of timing misalignment. The 1-dB tolerance of timing misalignment was around 7 ps (from -3.5 to $+3.5$ ps), for either conventional pure RZ-OOK OTDM or RZ-DPSK OTDM, respectively. With our proposed hybrid OTDM scheme, the 1-dB tolerance for RZ-OOK channels was greatly enhanced to around 14.5 ps. The tolerance for RZ-DPSK channels also had an obvious enhancement to 15 ps.

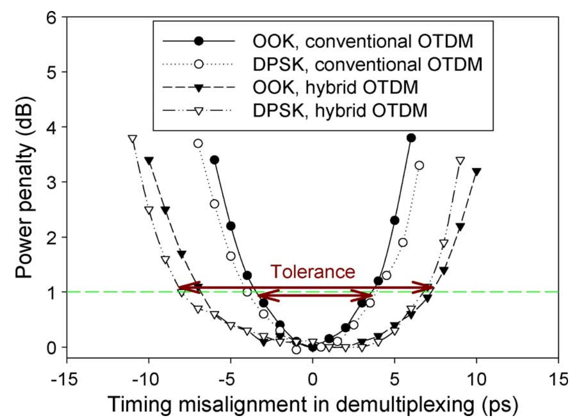

Fig. 5. Power penalty under condition of timing misalignment of a demultiplexed channel from conventional RZ-OOK OTDM signal (●), a demultiplexed channel from conventional RZ-DPSK OTDM signal (○), a demultiplexed OOK channel (▼), and a demultiplexed DPSK channel (▽) from hybrid 42.44-Gb/s OTDM signal, respectively.

V. Summary

By employing our proposed novel OTDM scheme with hybrid RZ-OOK and RZ-DPSK modulation formats, we have demonstrated that it could offer enhanced demultiplexing performance through a successful experiment of 84.88- to 10.61-Gb/s demultiplexing operated at normal conditions of a commercial EAM. Moreover, a 42.44-Gb/s demultiplexing experiment showed that the demultiplexing tolerance to timing misalignment could be doubled. Therefore, the requirements on the switching window and timing control of the demultiplexer could be greatly relaxed. The advantage of hybrid OTDM would be more significant in ultrahigh-speed (>160 Gb/s) OTDM demultiplexing, in which the performance is more sensitive to timing drift or timing jitter of the switching window.

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