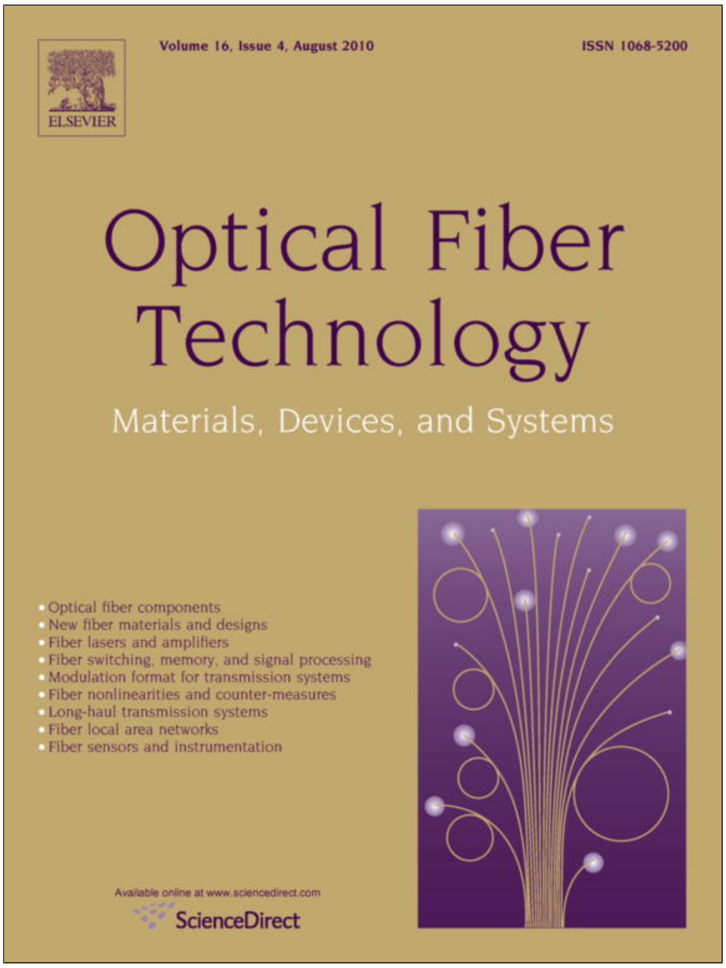
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Delay-interferometer based timing alignment monitoring for data and clock signal in optical RZ-DPSK and RZ-OOK systems

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ABSTRACT

A simple scheme for monitoring the alignment status between the pulse carver and the data modulator in both return-to-zero differential phase-shift keying (RZ-DPSK) and return-to-zero ON–OFF keying (RZ-OOK) systems is proposed and experimentally demonstrated. Not relying on any high-speed components, the scheme needs only an athermal delay-interferometer with properly designed delay and one or two optical power meters. For 10-Gb/s RZ-DPSK signals with a duty cycle of 50%, a large monitoring power dynamic range (MPDR) of ~13 dB was observed using differential monitoring. For 10-Gb/s RZ-OOK signals, the MPDR of ~2 dB was also observed. The feasibility of the proposed scheme for RZ-DPSK and RZ-OOK signals with a duty cycle of 33% was also investigated. The proposed scheme is also applicable to the single-modulator transmitter configuration, in which the data signal and the clock are mixed in the electrical domain.

1. Introduction

Recently return-to-zero (RZ) is the preferred data modulation format for long-haul high bit-rate wavelength-division multiplexed (WDM) optical transmission systems [1]. In such RZ systems RZ-DPSK and RZ-OOK are two dominant modulation formats, for which correct timing between pulse carving and data modulation must be maintained. Timing drift of 2–5 ps was observed when the temperature of the 1-m-long optical fiber between the pulse caver and the data modulator was changed by 50 °C, which may cause a power penalty of around 1 dB for an optically preamplified receiver in 40-Gb/s systems [2]. Thus an automatic alignment is necessary to compensate the timing drift between pulse carving and data modulation, due to temperature variation and device aging. On the other hand as such timing drift process is rather slow, it is possible to realize automatic alignment using cost-effective low-speed components.

Alignment monitoring is essential to realize the desired automatic timing alignment between pulse carving and data modulation. For RZ-DPSK systems, the timing-misalignment induced polarization variation in a polarization-maintaining fiber has been utilized as indicators for modulation alignment monitoring [2]. However, this scheme is polarization sensitive and has a limited monitoring power dynamic range (MPDR) of 0.2 dB. MPDR is the ratio between the two detected monitoring signal powers that correspond to the maximum and minimum timing misalignment. For a larger MPDR, a higher monitoring resolution can be attained. Another scheme utilizes an off-center optical filter to capture the frequency chirp due to the timing-misalignment, and the MPDR has been improved to 3.35 dB [3]. To further enhance the MPDR, an optical frequency discriminator and a microwave detector centered at half the data rate are used to monitor the spectrum broadening induced by timing misalignment [4], and an MPDR of 17 dB is achieved. However, a broadband photodetector capable of retrieving the data waveform is required. For RZ-OOK systems, it has been proposed to monitor the modulation alignment status by detecting the microwave power spectrum of the signal [5]. Similar with [4], a broadband photodetector is also required. Another scheme that is based on the chirping characteristic of the electro-absorption modulator (EAM) may not be applicable to other chirp-free modulators [6].

In this paper, we describe and experimentally demonstrate a simple modulation alignment monitoring scheme applicable to both RZ-DPSK and RZ-OOK systems using a delay-interferometer (DI) with properly designed delay. Not relying on any high-speed components, the scheme needs only an athermal DI and one or two optical power meters. It is applicable to any kinds of intensity modulator, and differential monitoring can further enhance the MPDR for RZ-DPSK systems. Because of the periodic wavelength response of the DI [7], the proposed scheme has potential for multichannel operation. As athermal DI has been commercially available [8,9], the proposed scheme becomes more practical.

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2. Operational principle

The operation principle is illustrated as follows. For simplicity, square waveform with a duty cycle of 50% is assumed for the obtained RZ pulse train. Zero rise- and fall-time is also assumed for both phase and amplitude modulation. The obtained RZ-DPSK (or RZ-OOK) signals are fed into a DI with 0.75-bit relative delay between the two arms. For such relative delay, the overlapped portions between the RZ-DPSK (or RZ-OOK) signals on different arms of the DI will be within half pulse width, as illustrated in Fig. 1. When the pulse carver and data modulator are well aligned, the overlapped portions of the signals in the two arms may carry different signals (different phases for RZ-DPSK signals and different amplitudes for RZ-OOK signals). In contrast, when the pulse carver and data modulator have half-bit misalignment, the overlapped portions must carry the same signal. Such difference will induce power variation through interference at the output ports of the DI and thus can be utilized as indicators for modulation alignment monitoring.

The question now is how to determine the optimal relative delay between two arms of the DI to maximize the MPDR for both constructive port (CP) and destructive port (DP). Under the aforementioned assumption of square waveform and instantaneous data transition, it is found, through simple calculation, that the optimal relative delay should be $\tau/2$ or $T - \tau/2$, where τ is the pulse width and T is the bit period.

Furthermore, for RZ-DPSK signals shown in Fig. 1, the signal symbols '0' and 'π' are assumed to be equally probable. For the aligned case, both ports of the DI have the same average power, due to the fact that the overlapped portions generate complementary output at each port of the DI via constructive or destructive interference. Thus, if differential monitoring (DM) (using the power difference between the two output ports of the DI for alignment monitoring) is used, theoretically, the MPDR can reach infinity as the minimum monitoring power is 0. It should be noted such differential monitoring is quite different from the well-known balanced detection for DPSK demodulation, where strict timing alignment between two photodetectors is required. Since the drift of the timing between pulse carver and data modulator occurs on the time scale of tens of minutes [6], the implementation of such differential monitoring requires neither broadband photodetectors nor precise timing alignment between the two optical power meters.

For practical systems with non-square pulse waveform and non-zero rise/fall-time for data modulation, simulation using OptSim™ is conducted to find the optimal relative delay for 10-Gb/s RZ-DPSK and RZ-OOK signals with duty cycle of 50%. In the simulation, all the parameters (say rise- and fall-time) are set according to the specifications of the devices used in the following experiment. The simulation result is shown in Fig. 2. From it we can conclude that the destructive port has larger MPDR than the constructive port for both RZ-DPSK and RZ-OOK systems, thus the destructive port should be used for single-port monitoring. DM can further enhance the MPDR from less than 2 dB to ~14 dB for RZ-DPSK signals.

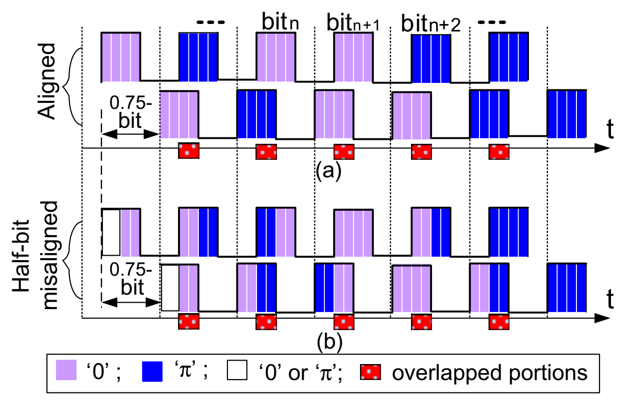

Fig. 1. RZ-DPSK signals in the two arms of the DI before combining by the output 3-dB coupler for (a) aligned and (b) half-bit misaligned cases.

3. Experimental demonstration

Fig. 3 shows the experimental setup used to investigate the proposed scheme. A CW light at 1549 nm was carved into a 10-Gb/s pulse train with a pulse width of 50 ps and rise-time of ~15 ps via a Mach–Zehnder intensity modulator (MZM), driven by a 10-GHz sinusoidal clock signal. The pulse train was then modulated with a 10-Gb/s $2^{31} - 1$ Pseudorandom binary sequence (PRBS) using a $LiNbO_3$ phase modulator (PM) or MZM to generate the RZ-DPSK or RZ-OOK signal. A tunable electrical delay was used to provide different timing misalignments between the pulse carver and the data modulator. At the output of the PM or MZM, a portion of optical power was tapped off and fed into a DI with ~94-ps relative delay for alignment monitoring. The inset in Fig. 3 shows the eye diagrams of the detected RZ-DPSK signals from each port of the DI when the pulse carver and data modulator are well aligned or have half-bit misalignment. When it is aligned, the constructive port and the destructive port should have nearly the same output monitoring power (assume '0' and 'π' are equally probable), since their output signals are complementary. As the timing misalignment increases, for the destructive port, the output monitoring power will decrease due to the dip in the middle of the eye diagram. At the same time the output monitoring power will increase for the constructive port from the principle of conservation of energy. The experimental results on MPDR are shown in Fig. 4. When differential monitoring is used for the RZ-DPSK signal, the power difference between the DI's two output ports monotonously increases as the absolute value of the timing misalignment increases. Thus, the timing misalignment of the RZ-DPSK signal can be confined by stepwise dithering the timing alignment and minimizing the power difference between the DI's two output ports through a feedback circuit. On the other hand, when single-port monitoring is used for RZ-DPSK/RZ-OOK signals, the DI's output monitoring power, from the destructive port, monotonously decreases as the absolute value of the timing misalignment increases. Thus, the tim-

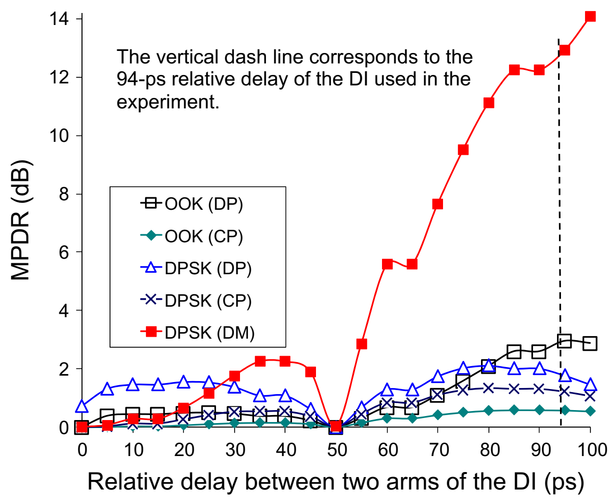

Fig. 2. MPDR versus the delay of DI. The duty cycle of the RZ pulse train in simulation was 50%. DP: destructive port, CP: constructive port, and DM: differential monitoring.

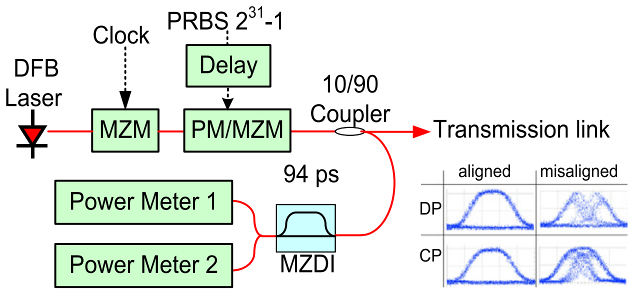

Fig. 3. Experimental setup. Inset: Eye diagrams of the detected RZ-DPSK signals from each port of the DI when the pulse carver and data modulator are well aligned or have half-bit misalignment. Time scale: 20 ps/div. DP: destructive port and CP: constructive port.

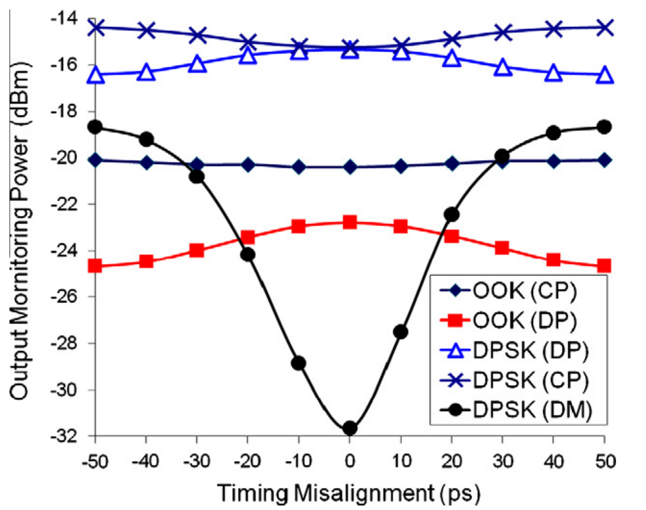

Fig. 4. Experimental results of output monitoring power for different timing misalignments using 94-ps DI.

ing misalignment can be confined by stepwise tuning the timing alignment and maximizing DI's output monitoring power through a feedback circuit. For RZ-DPSK (RZ-OOK) signals, the MPDR of ~1.2 dB (~2 dB) and ~0.9 dB (~0.3 dB) are observed for the destructive port and the constructive port, respectively. Compared with the points intersected by the dash line (~94-ps delay) in Fig. 2, these experimental results are slightly smaller than those in the simulation, due to the limited accuracy in the simulation parameter value selection based on our devices. Overall, the experimental and simulation results agree well. When differential monitoring is used, the MPDR for RZ-DPSK systems is effectively improved to 13 dB, which also agrees well with the simulation result of 12.9 dB. The differential monitoring case has better agreement between the experimental and the simulation results, compared to the single-port cases, as some common errors in the two ports are rejected by differential monitoring.

For the proposed scheme, we also investigated its tolerance to temperature-induced frequency offset of the 94-ps DI through simulation. For the athermal DI in [8], the temperature-induced frequency offset is <±0.5 GHz over the range of [0, 70 °C]. Within such a small frequency offset, only 0.33-dB MPDR degradation is observed when the RZ-OOK signal is monitored by DI's destructive port, whereas the MPDR degradation is less than 0.1 dB for the other four cases. In addition, when differential monitoring is used for the RZ-DPSK signal, within such a small frequency offset, the power difference between DI's two output ports still monotonously increases as the absolute value of the timing misalignment increases. Thus, the timing misalignment of the RZ-DPSK signal can be confined by stepwise dithering the timing alignment and minimizing the power difference between DI's two output ports through a feedback circuit. Similarly, when the destructive prot is used for single-port monitoring, the timing misalignment can be minimized by maximizing the DI's output monitoring as in the aforementioned discussion.

For RZ-DPSK signals, the power difference between the two output ports of the DI decreases as the timing misalignment is reduced, as shown in Fig. 4. With no timing misalignment, the power difference is nearly vanished. Thus, differential monitoring can significantly enhance the MPDR for RZ-DPSK signals. For RZ-OOK signals, however, although the power difference between the two output ports of the DI also decreases as the timing misalignment reduces, the minimum value of the power difference is not very small and cannot effectively enhance the MPDR by DM. Thus, differential monitoring is only applicable to RZ-DPSK signals.

We then investigated the feasibility of the proposed scheme for RZ signals with a duty cycle of 33% through simulation. Raised-cosine pulse was assumed in the simulation. We also studied the relationship between MPDR and the delay of DI as shown in Fig. 5. When the destructive port is used for single-port monitoring, the MPDR for the RZ-OOK signal is around 3.6 dB with an optimal delay of ~95 ps, whereas the MPDR for the RZ-DPSK signal is around 2.4 dB with an optimal delay of ~86 ps. The MPDR for the RZ-DPSK signal is significantly enhanced to ~34 dB by differential monitoring, with an optimal delay of 100 ps.

The mixing between the data signal and the clock for RZ signal generation could also be done in the electrical domain to save the modulator used as the pulse cover. The AND operation between the data signal and the clock can generate RZ-shaped driving signal to drive a single MZM for the generation of RZ-OOK signal [10]. RZ-DPSK signal could also be generated by a single MZM with specially designed driver electronics [11]. In both schemes, timing misalignment between the data signal and the clock signal will degrade the obtained RZ-OOK/RZ-DPSK signals. The proposed monitoring scheme can also be applied to these single-modulator schemes. We investigated the relationship between MPDR and the delay of DI through simulation, as shown in Fig. 6. When the destructive port is used for single-port monitoring, the MPDR for the 10-Gb/s RZ-OOK signal is around 2.8 dB with an optimal delay of ~95 ps,

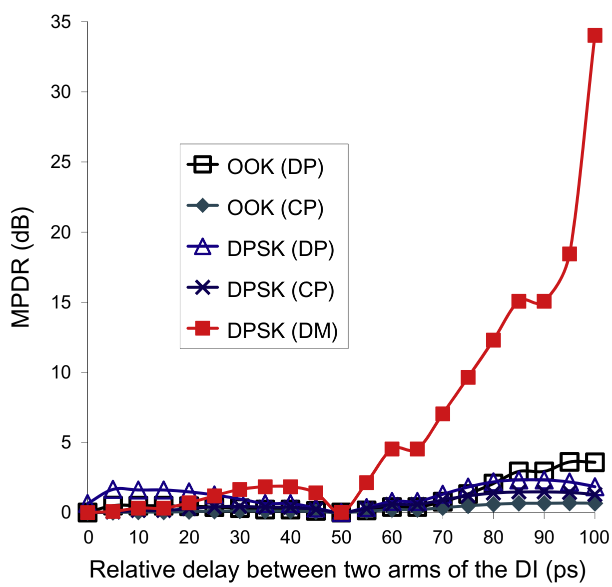

Fig. 5. MPDR vs. the delay of DI. The duty cycle of the RZ pulse train in simulation was 33%. DP: destructive port, CP: constructive port, and DM: differential monitoring.

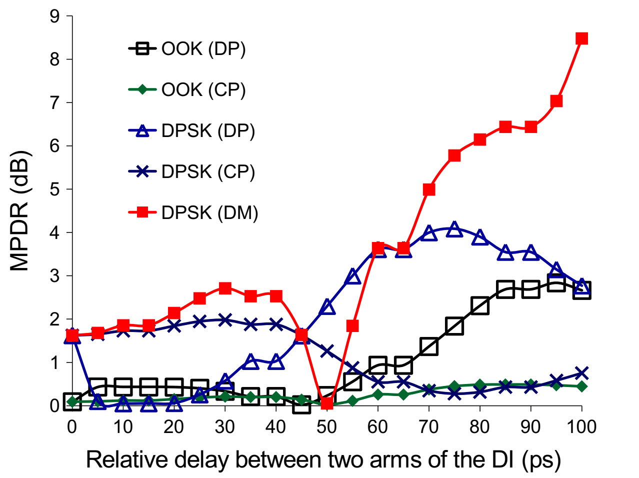

Fig. 6. MPDR versus the delay of DI when the RZ-DPSK/RZ-OOK signals are generated by single-modulator. DP: destructive port, CP: constructive port, and DM: differential monitoring.

whereas the MPDR for the 10-Gb/s RZ-DPSK signal is around 4 dB with an optimal delay of ~75 ps. The MPDR for the 10-Gb/s RZ-DPSK signal is enhanced to ~8.5 dB by differential monitoring, with an optimal delay of 100 ps. It is noteworthy that for these single-modulator schemes, even without using the proposed monitoring scheme the timing-misalignment-induced power variation in the MZM output still has a 1.6-dB and a 0.12-dB MPDR for the 10-Gb/s RZ-DPSK and RZ-OOK signal, respectively. By using the proposed monitoring scheme, the MPDR can be improved by 6.9 dB and 2.68 dB for the RZ-DPSK signal and the RZ-OOK signal, respectively.

4. Conclusion

We have proposed and demonstrated a simple scheme for monitoring the alignment status between the data and the clock signal for the generation of RZ-DPSK and RZ-OOK signals. Not relying on any high-speed components, the proposed scheme needs only an athermal delay-interferometer and one or two optical power meters. The scheme also has potential for multichannel operation, because of the periodic wavelength response of the DI. The proposed scheme is first applied to the transmitter configuration using cascaded data modulator and pulse carver. For 10-Gb/s RZ-DPSK signals with a duty cycle of 50% and 33%, by differential monitoring, the MPDR was significantly improved to ~13 dB and ~34 dB, respectively. For 10-Gb/s RZ-OOK signals, the MPDR of ~2 dB and ~3.6 dB were obtained for the duty cycle of 50% and 33%., respectively. The proposed scheme is also applicable to the single-modulator transmitter configuration, in which the data signal and the clock are mixed in the electrical domain. The MPDR for the 10-Gb/s RZ-DPSK and RZ-OOK signals is enhanced to 8.5 and 2.8 dB, respectively, by using the proposed scheme.

Acknowledgment

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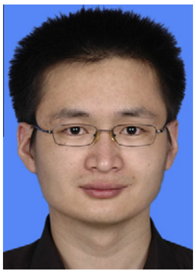

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