Spectrum-efficient 80-Gbit/s differential phase-shift keying transmitter using phase-interleaving technology without optical-time or polarization-division multiplexing

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Abstract. We experimentally demonstrate a spectrum-efficient 80-Gbit/s differential phase-shift keying (DPSK) transmitter for a single wavelength channel using phase-interleaving technology without any optical-time or polarization-division multiplexing. Two cascaded independent 40-Gbit/s modulations were time-interleaved to generate an 80-Gbit/s DPSK signal with a compact spectrum. The proposed 80-Gbit/s DPSK transmitter consists of two independent 40-Gbit/s phase modulators only. No additional high-speed pre- or postcoder is required at the transmitter or receiver side. The proposed scheme is potentially cost-effective.
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1 Introduction

In high-speed optical transmission systems, spectrum efficiency and per-channel capacity should be enhanced in order to reduce the implementation cost per bit as well as transmission impairment. Electrical or optical time-division multiplexing (ETDM, OTDM) has been widely employed to increase the per-channel capacity, and advanced modulation formats and polarization-division multiplexing (PDM) have been used to increase spectrum efficiency. A promising candidate for future optical transmission systems is differential phase-shift keying (DPSK), which offers improved receiver sensitivity and higher tolerance against nonlinear optical effects.[1–3] Recently, a single-channel DPSK system with bit rate of more than 640 Gbit/s has been successfully demonstrated using OTDM and PDM.[4] In that system, however, the transmitter employed before multiplexing is operated at only 40 Gbit/s, which indicates that the achievable capacity per wavelength is still limited by the available electronics.

To further increase the transmission capacity with a compact spectrum, it is desirable to explore novel transmitters with high capacity and spectrum efficiency. In this letter, we propose and describe an experimental demonstration of a cost-effective and spectrum-efficient 80-Gbit/s DPSK transmitter using phase-interleaving technology to enhance the spectrum efficiency as well as the per-channel capacity. The proposed high-speed DPSK transmitter offers the following advantages: (1) It is cost-effective, because the implementation is based on two cascaded low-speed phase modulations. (2) For the demonstrated 80-Gbit/s phase-interleaved DPSK signal, a 20-dB bandwidth of only 0.68 nm was observed, which promises high spectrum efficiency. (3) It does not require any additional encoders or complicated ETDM, OTDM, or PDM devices at the transmitter and receiver sides.

2 Operation Principle

Figure 1 illustrates the proposed DPSK transmitter using phase-interleaving technology. Continuous wave (CW) light from a laser diode is independently phase-modulated by two cascaded phase modulators. Here we assume that the bit period of each stage of the phase modulation is T. After the first-stage modulation, the phase of the light is remodulated in the subsequent stage with a relative time offset. The offset can be tuned by using an optical or electrical delay line. As an example, phase patterns before and after phase interleaving are shown in Fig. 2(I). The two phase modulations at a bit rate of $1/T$ [Fig. 2(a) and 2(b)] are time-shifted with a relative offset $T/2$, and the resultant final phase pattern [Fig. 2(c)] after phase interleaving is logically equivalent to the result of an XOR operation between the two independent phase modulation patterns that are applied. At the same time, the modulation speed of the resultant phase modulation is doubled to $2/T$ compared with that of the individual phase modulation, $1/T$. Thus, a high-speed DPSK signal with bit rate of $2/T$ is generated using components operating at a lower bit rate $(1/T)$.

Interestingly, although the final phase pattern is logically the result of an XOR operation between the two individual phase modulations, the two channels can be simply and independently separated at the receiver side using an optical or electrical demultiplexer. The generated high-speed DPSK signal can also be directly detected by using a high-speed ETDM-based optical receiver.[5] At the transmitter side, the precoders for two channels are independently operated at lower bit rate, $1/T$. As shown in Fig. 2(II), the two phase modulations, ϕ_1 and ϕ_2, are introduced by the cascaded phase modulators, respectively. We assume that the phase patterns of ϕ_1 and ϕ_2 at time slots i and $i-1$ are ϕ_{1_i}, $\phi_{1\_(i-1)}$, and ϕ_{2_i}, $\phi_{2\_(i-1)}$, respectively. As shown in Fig. 2(f), the corresponding resultant phase pattern, ϕ_3, at time slots $2i$ and $2i-1$ is obtained from the XOR operation between the phase patterns ϕ_1 and ϕ_2 at time slots i and $i-1$. The resultant phase ϕ_3 at time slots $2i$ and $2i-1$ is given by

$$\phi_{3\_(2i)} = \phi_{1\_i} \oplus \phi_{2\_(i-1)} \quad \text{and}$$
$$\phi_{3\_(2i-1)} = \phi_{1\_(i-1)} \oplus \phi_{2\_(i-1)}. \tag{1}$$

At the receiver side, a Mach-Zehnder delay interferometer (MZDI) with $T/2$ relative delay between the two arms is employed for phase demodulation. Thus, after the phase

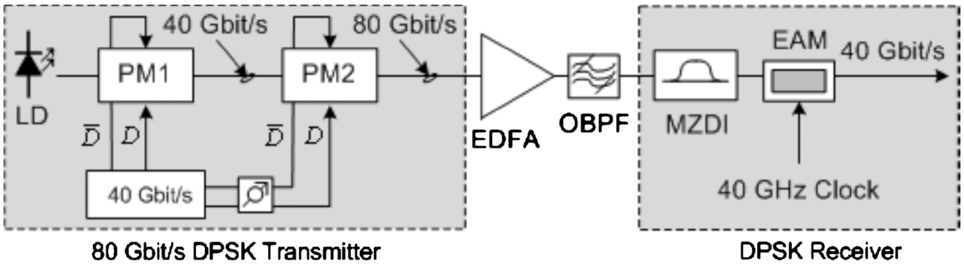

Fig. 1 The proposed cost-effective DPSK transmitter using phase-interleaving technology. PM: phase modulator; OBPF: optical bandpass filter; MZDI: Mach-Zehnder delay interferometer; EAM: electroabsorption modulator.

demodulator, the demodulated data at time slot $2i$, $k_{3\_(2i)}$, will be

$$k_{3\_(2i)} = \phi_{3\_(2i)} \oplus \phi_{3\_(2i-1)} = \phi_{1\_i} \oplus \phi_{1\_(i-1)}. \tag{2}$$

This indicates that the demodulated data $k_{3\_(2i)}$ are dependent only on the first-stage phase modulation applied in the transmitter. Similarly, the demodulated data at time slot $2i-1$, $k_{3\_(2i-1)}$, are obtained as

$$k_{3\_(2i+1)} = \phi_{2\_i} \oplus \phi_{2\_(i-1)}. \tag{3}$$

It is clear that the demodulated data at time slot $2i+1$ result from the second-stage phase modulation at the transmitter side only. Therefore, although the two serially cascaded phase modulations are interleaved in the phase domain, after the phase demodulation, the obtained data are a simple multiplexing of the two channels in the time domain with double the bit rate. Moreover, the differential precoders for the two tributaries are also operated independently at the lower bit rate $(1/T)$ rather than the resultant bit rate $(2/T)$. No additional high-speed pre- or postcoder is required at the transmitter or receiver side. This further simplifies the configuration of the transmitter and reduces the implementation cost.

3 Experiments and Results

An 80-Gbit/s DPSK transmitter using phase interleaving was experimentally demonstrated to verify the proposed scheme. The experiment setup was similar to that illustrated in Fig. 1. The 80-Gbit/s DPSK transmitter consisted of a laser source and two cascaded dual-drive Mach-Zehnder modulators, which were driven by 40-Gbit/s $10^{31}-1$ pseudorandom binary sequence (PRBS) data in push-pull operations with a peak voltage of $2V_\pi$ to introduce phase modulations. The 3-dB bandwidth of the employed modulators' frequency response was only 23 GHz. A tunable electrical delay line was inserted before driving the second phase modulator to ensure a 12.5-ps relative time offset between the two phase modulation tributaries after phase interleaving. At the receiver side, a MZDI with a free spectral range of 164 GHz was employed to demodulate the DPSK signal. After demodulation, an electroabsorption modulator (EAM) driven by a 40-GHz clock signal was employed to demultiplex the detected 80-Gbit/s data to 40-Gbit/s data.

The eye diagrams of demodulated 80-Gbit/s data and 40-Gbit/s data after demultiplexing were measured by a high-speed optical sampling oscilloscope and are shown in Fig. 3. The nonuniform eye opening was mainly due to the performance differences between the phase modulators. The measured optical spectrum of the generated 80-Gbit/s phase-interleaved DPSK signal is illustrated in Fig. 4. The optical spectrum of a single-stage 40-Gbit/s DPSK signal is also depicted for comparison. The 20-dB spectral bandwidth of the generated 80-Gbit/s phase-interleaved DPSK was only 0.68 nm, whereas that of the conventional 40-Gbit/s DPSK signal was around 0.44 nm. This indicates that the generated DPSK signal using phase interleaving offers higher spectrum efficiency than the conventional DPSK signal.

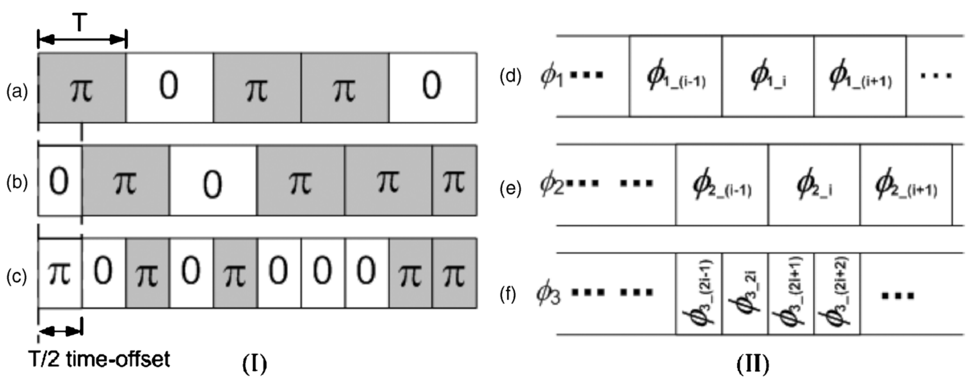

Fig. 2 Operation principle of proposed phase-interleaving technology.

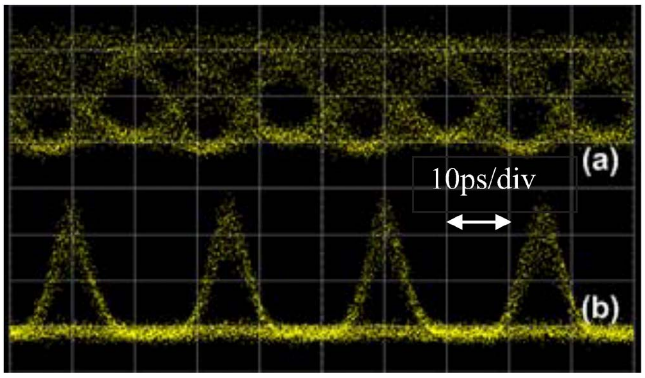

Fig. 3 Eye diagrams of detected (a) 80-Gbit/s DPSK signal after MZDI and (b) 40-Gbit/s data after demultiplexing (10 ps/div).

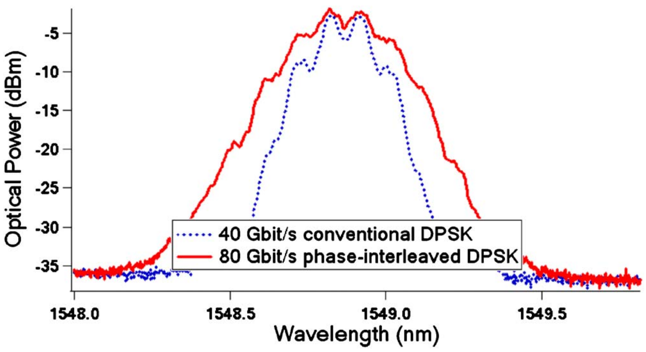

Fig. 4 Optical spectra of 40-Gbit/s conventional DPSK signal and 80 Gbit/s phase-interleaved DPSK signal.

4 Conclusion

We experimentally demonstrated a cost-effective and spectrum-efficient 80-Gbit/s DPSK transmitter using phase-interleaving technology. The two independent phase modulations were logically combined through an XOR operation with a relative time offset, resulting in the final phase pattern with double the bit rate. Moreover, the proposed DPSK transmitter had a compact spectrum compared with conventional DPSK signals. A 20-dB bandwidth of only 0.68 nm was observed for the 80-Gbit/s phase-interleaved DPSK signal.

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