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一种无需相位比较器的超高速光时分复用系统的自时钟恢复方法

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摘　要：基于带内时钟导引的置入与提取，提出一种在超高速时分复用系统中的自时钟恢复方案. 通过在发送端插入带内时钟导引并在接收端提取出该时钟导引，实现系统时钟的瞬时同步恢复，无需传统时钟恢复中的超快相位比较器和锁相环. 实验分别演示了由相位调制和强度调制构造的时钟导引，结果表明所提方法可实现 160～40 Gb/s 的无误码解复用. 该方法在光发射机之后和光接收机之前的光域内对数据信号进行预处理，简化了时钟恢复，同时并未改变光发射机和光接收机的原理、结构和设计，与现行的光纤通信系统兼容.

关键词：光时分复用；自时钟恢复；带内时钟导引；光相位比较器；微波光子学

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Phase-comparator-free Self-clocking for Ultra-high-speed Optical Time-division Multiplexing System

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Abstract: A novel clock recovery scheme based on in-band pilot insertion and extraction was demonstrated for ultra-high bit rates Optical Time-Division Multiplexing (OTDM) system. The clock recovery function was realized by inserting and extracting an in-band clock pilot located in the data spectrum, which did not need any ultra-fast phase comparator or phase-locked loop in the receiver. The scheme allowed fast synchronization, low timing jitter and highly stable recovered clock for OTDM receivers. The clock pilot was constructed with phase modulation and intensity modulation, respectively, which showed error-free operation of 160-to-40 Gb/s demultiplexing. The proposed method simplfies clock recovery configuration throught pre-processing of data signal in the optical domain between optical transmitter and receiver, which is compatabile with standard OTDM system after minor modification of optical transmitter and receiver.

Key words: Optical time-division multiplexing; Clock recovery; In-band clock pilot; Optical phase-comparator; Microwave photonics

OCIS Codes: 060.2360; 060.2330; 060.5625

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0 Introduction

In an Optical Time-Division Multiplexing (OTDM) transmission system, it is necessary to recover a base-rate clock of the received OTDM data signal[1], which is required for accessing the tributaries, such as optical demultiplexing and time-division add-drop multiplexing. The recovered clock can be in the form of an electrical sinusoidal signal or an optical pulse train[2]. The basic problem of clock recovery lies in that a perfectly multiplexed OTDM data signal does not contain any base-rate component for direct extraction. Therefore, typical clock recovery schemes involve a pre-scaled clock running at a frequency near the base-rate, and the clock recovery will then tune the frequency of the pre-scaled clock and phase-lock it to the OTDM signal, which requires a phase comparison between the pre-scaled clock and the OTDM signal to output an error signal to control the Phase-Locked Loop (PLL). As the bit rate goes up to beyond 100 Gbit/s, an optical phase comparison becomes necessary due to the limited response time of the electrical phase comparison[1]. Different nonlinearties such as four-wave mixing[3] or cross-phase modulation[4-5] in semiconductor optical amplifier, three wave-mixing in a Periodically-Poled Lithium Niobate (PPLN) waveguide[6] or electro-absorption modulation[7-9] or cascade intensity modulation[10], have been exploited to provide the optical phase comparator functionality. Nevertheless, the major difficulty of these approaches is that a PLL is required to accomplish the synchronization whose phase comparator must hold a very high time-resolution of the order of the bit-slot duration.

In this paper, a phase-comparator-free clock recovery scheme is proposed for high-speed OTDM system, which consists of inserting a base-rate clock pilot signal at the transmitter, and extracting this pilot signal at the receiver. The pilot signal is located within the 20 dB bandwidth of the data spectrum. The clock signal is recovered by spectrally separating the in-band pilot from the OTDM data and converting to electrical waveform after photodetection. We experimentally demonstrate the clock recovery scheme exploiting the phase-modulated pilot and the intensity-modulated pilot, respectively. The comparison of both pilot formats is summarized and given in the conclusion.

1 Phase-modulated pilot for self-clocking

The proposed clock recovery based on the phase-modulated pilot is shown in Fig. 1. MUX is Optical

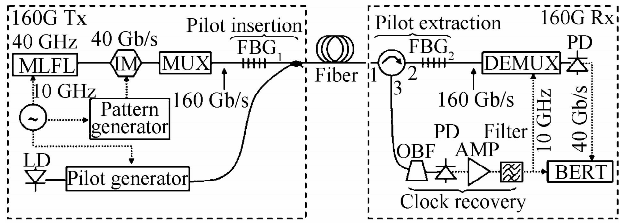


Fig. 1 Schematic configuration of self-clocking scheme

Time-domain Multiplexer, FBG is Fiber-Bragg Grating, OBF is Optical Bandpass Filter, PD is Photodetector, DEMUX is Demultiplexer, BERT is Bit-error rate tester. In the experiment, the data signal is generated by a Mode-Locked Fiber Laser (MLFL) at the repetition frequency of 40 GHz tuned to 1 555.86 nm. The pulses are RZ On-Off Keying (OOK) modulated with a Pseudo-Random Bit Sequence (PRBS) of 2^7-1 at one single polarization and subsequently multiplexed up to 160 Gb/s through a polarization-maintaining fiber-delay multiplexer. The 160 Gb/s data signal is then filtered by an optical Fiber Bragg-Grating (FBG_1) to carve the data spectrum for the clock pilot. The pilot is generated by a CW laser tuned to 1 558.93 nm which is phase modulated at 10 GHz by the master clock. The wavelength of the pilot is offset by 3.07 nm with respect to the data carrier, which is located between two adjacent 160 GHz spectral lines so as to avoid crosstalk with the data signal. The driving power is optimized to intensify the first order sidebands produced by the phase modulation, which is corresponding to an optimized modulation index of 1.07[11]. Subsequently, the phase modulated signal is inserted in the data signal band via an Optical Coupler (OC). In the receiver end, the in-band pilot is extracted at port 3 of the circulator by means of a Fiber Bragg-Grating (FBG_2). Both FBG_1 and FBG_2 are centered at 1 558.93 nm and have same bandwidth of 0.4 nm. Later on, a tunable optical bandpass filter is used to select the optical carrier and the first-order upper sideband, and thus the clock is recovered by optical mixing detection associated to a Photodetector (PD)[11] and then amplified and filtered by an electrical high Q band-pass filter. Finally, the data signal after pilot extraction and the recovered clock are used as an input and driver of the EAM demultiplexer, respectively, in order to perform Bit-Error-Rate (BER) tests on the tributaries.

Fig. 2(a) illustrates the optical spectrum of the pilot inserted in the data signal band. The inset shows the 160 Gb/s traces after pilot insertion. It is obvious that the eye-diagram of the date signal becomes degraded because of the pilot insertion.

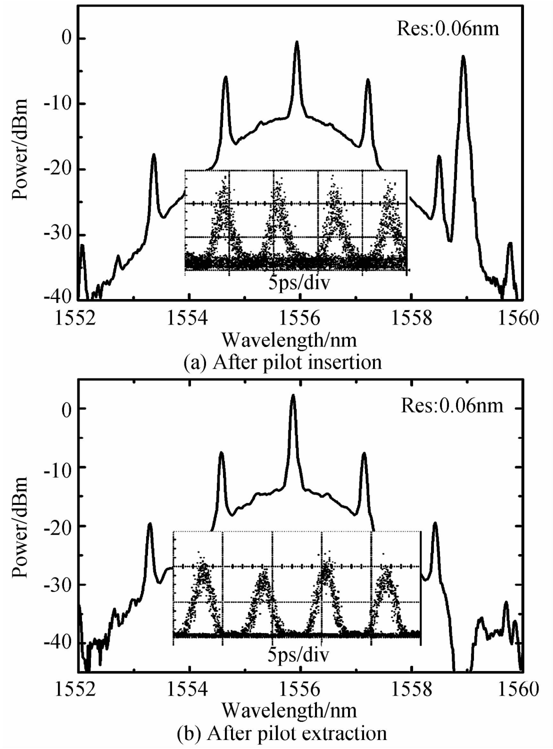


Fig. 2 Optical spectrum and eye diagram of the data signal in the case of phase-modulated pilot for clock recovery

In the receiver end, the extraction of the pilot creates a carve in the data signal spectrum as depicted in Fig. 2(b). The extracted pilot is filtered by an OBPF with 0.25 nm bandwidth to select the pilot carrier and its first-order upper sideband for clock recovery.

To evaluate the proposed clock recovery technique, the clock frequency is quadrupled to 40 GHz and in turn used to drive the EAM demultiplexer in order to extract 40 Gb/s tributaries. In Fig. 3, the open circles illustrate the BER performance of the four extracted channels corresponding to the back-to-back configuration employing the master clock. Error-free operation is achieved with a received power of −12.1 dBm. The filled squares represent the BER performance of the data after pilot insertion and extraction employing the

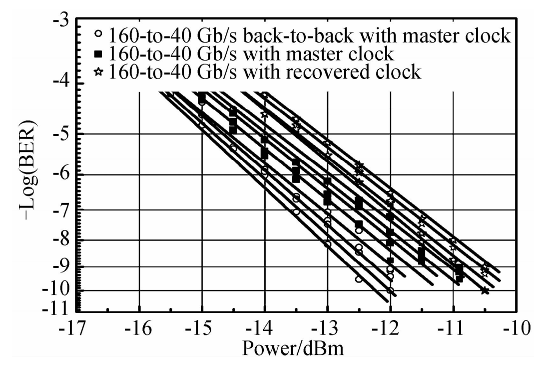


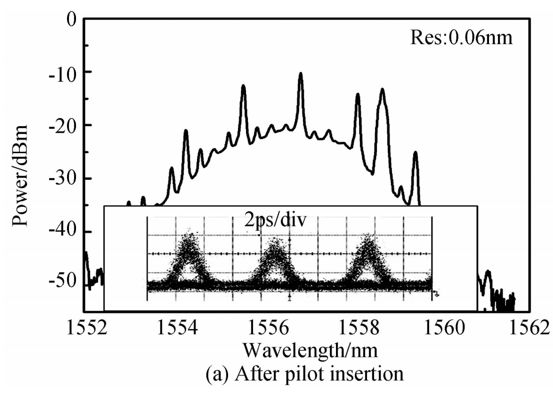
Fig. 3 BER performances of the 40 Gb/s tributaries using the phase-modulated clock pilot

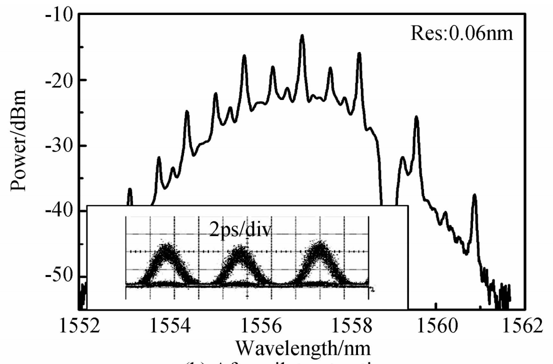
master clock, where the configuration employing the recovered clock shows an error-free performance with a received power of −10.5 dBm. This turns out in a power penalty of 1.6 dB, which includes the clock pilot insertion, extraction and clock recovery. Moreover, the difference between the case employing the recovered clock and that employing the master clock indicates that the degradation of the clock only introduces a power penalty of 0.5 dB.

2 Intensity-modulated pilot for self-clocking

According to the aforementioned proof-of-concept experiment, we demonstrate a much detailed clock recovery with an intensity-modulated pilot[12-13]. In the second experiment, the wavelength of the MLFL is tuned to 1 557.00 nm, and then the 160 Gb/s data signal is coupled into the FBG_1 for pilot insertion. The central wavelength of the FBG_1 is located at 1 558.93 nm ($\Delta\lambda = 1.93$ nm with respect to the data carrier) to avoid crosstalk, which is much closer to the central wavelength of data carrier compared to the first experiment. The pilot is generated by modulating a CW laser with the 10 GHz master clock. The bias and driving power are optimized to suppress high-order harmonics and to keep a linear intensity modulation as much as possible. Finally, the pilot is combined with the 160 Gb/s data through an optical coupler.

The carved data-spectrum and the inserted pilot in the signal spectrum are shown in Fig. 4(a). The 160 Gb/s data and the 10 GHz pilot are transmitted together through a dispersion-managed fiber link consisting of 51 km of standard Single-Mode Fiber (SMF) and a Dispersion Compensation Module (DCM). In the receiver part, the co-propagated data and pilot are separated via an optical circulator and the FBG_2. A tunable optical bandpass filter is used to select the optical carrier and the both first-order sidebands due to the intensity modulation. The data after pilot extraction, in port 2, is shown in Fig. 4(b). The extracted clock pilot is converted to the electrical domain by a photodiode followed by a transimpedance





(b) After pilot extraction

Fig. 4　Optical spectra and waveforms of the data signal in the case of intensity-modulated pilot for clock recovery

amplifier whose output is fed to a bandpass filter and then quadrupled (×4) to form a 40 GHz clock that drives the EAM-based demultiplexer.

Because the pilot and the data are synchronized in the transmitter and are spectrally located close to each other, they are affected by the same fiber impairments leading to the same phase drifts. Therefore, the relative phase difference between clock and data is preserved along the fiber links. We measure the phase noise and timing jitter of the recovered clock after transmission using different data patterns: 2^7-1, $2^{15}-1$ and $2^{31}-1$, and obtain timing jitters of approximately 260 fs, proving that the self-clocking concept is not pattern-length dependent [12].

Further, we use the recovered clock to drive an EAM-based demultiplexer, and carry out BER measurements on the extracted tributaries. The BER performance of the system is described in Fig. 5. The open circles illustrate the 160-to-40 Gb/s in the back-to-back configuration used as a reference, whereas the open stars represent 160-to-40 Gb/s the case after transmission. Error-free operation is achieved on all the channels with an average received power of −10.9 dBm. This value corresponds to an average power penalty of 1.2 dB between the reference and the case after transmission. This penalty is mainly due to the carving effect of the FBGs on the data signal.

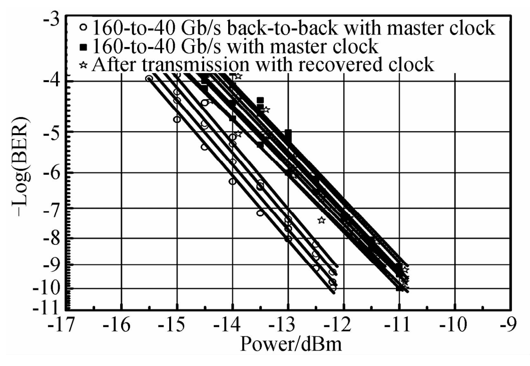


Fig. 5　BER curves of the 40 Gb/s tributaries using the master clock and the recovered clock

At the same time, the intensity-based pilot show a decrease of 0.4 dB power penalty compared to the phase-based pilot, which comes from the off-centered tunable optical bandpass filter for the phase-modulation-to-intensity-modulation conversion. The used OBF has a 3 dB bandwidth of 0.18 nm, and 20 dB bandwidth of 0.5 nm with 0.15 nm off-centered to the pilot wavelength.

3　Conclusions

A novel phase-comparator-free clock recovery is demonstrated based on inserting at the transmitter and extracting at the receiver a clock pilot which is located in the data spectrum. The clock pilot is constructed and verified by phase modulation format and intensity modulation format, respectively. Both schemes have very similar configuration and performance, which allow fast synchronization, low timing jitter, and highly stable clock recovery without any ultra-fast phase comparator and PLL in the receiver. The main difference lies in the pilot format, one is phase-modulated pilot, and the other is intensity-modulated pilot. Phase modulation is bias-drifting free, and needs phase modulation-to-intensity modulation conversion. However, the intensity modulation can be directly detected, and needs to overcome the bias drifting problem.

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