Feasibility Study of 0.8-b/s/Hz Spectral Efficiency at 160 Gb/s Using Phase-Correlated RZ Signals With Vestigial Sideband Filtering

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***Abstract*—We study the feasibility of achieving 0.8-b/s/Hz spectral efficiency at 160 Gb/s. We generate phase-correlated return-to-zero (RZ) signals by utilizing the Kerr shutter effect in a highly nonlinear fiber. The 160-Gb/s RZ signal is then filtered with a 200-GHz bandwidth filter. Error-free operation is obtained by properly shifting the central wavelength of the filter. We also investigate the filtering performance of phase-uncorrelated signals generated by conventional optical time-division multiplexing means.**

***Index Terms*—Optical filters, optical Kerr effect, phase coding, spectral analysis.**

I. INTRODUCTION

ULTRAHIGH-SPEED transmission systems (>40 Gb/s) are attractive for next-generation communication infrastructures. With the same capacity in wavelength-division-multiplexed (WDM) transmission, high bit-rate systems offer a reduced number of wavelength channels to minimize the equipment footprint and power consumption, simplify the network management, and lower the cost per bit by employing high-speed terminals. In addition, to further increase the capacity of a transmission system within the existing amplifier bandwidth, improving the spectral efficiency of the signals is an effective approach. A previous experiment has shown 160-Gb/s WDM transmission with a spectral efficiency of 0.33 b/s/Hz [1]. Furthermore, a high spectral efficiency of 0.53 b/s/Hz was also demonstrated [2]–[4]. In all these experiments, optical time-division multiplexing (OTDM) was used to obtain 160-Gb/s return-to-zero (RZ) signals, in which optical phases of adjacent bits are uncorrelated. A further improvement in the spectral efficiency using narrow-band filters is limited due to the fact that the random and drifting phases between the adjacent broadened pulses result in an unstable bit-error rate (BER) and significantly degrade the system performance. Higher spectral efficiency could be achieved by using strong filtering of certain phase-correlated modulation formats, for example, nonreturn-to-zero (NRZ) with vestigial sideband (VSB) filtering [5], carrier-suppressed RZ (CSRZ) [6], and CSRZ with differential phase-shift keying (DPSK) [7], all demonstrated at 40 Gb/s due to the unavailability of phase-correlated signal generation beyond 40 Gb/s.

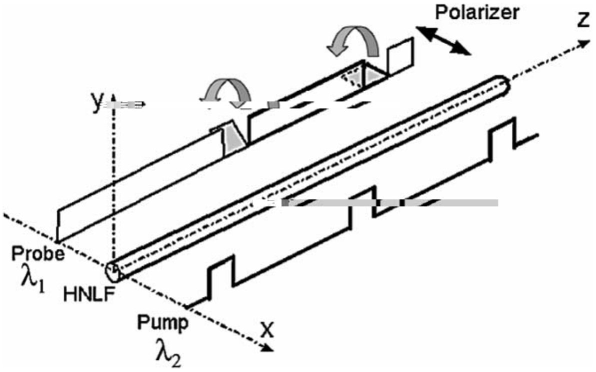

Fig. 1. Principle illustration of the conversion from phase-uncorrelated OTDM signal to phase-correlated signal through nonlinear polarization rotation.

In this letter, we investigate the VSB filtering performance of a 160-Gb/s phase-correlated RZ signal through a rectangular-shaped bandpass filter having a 200-GHz bandwidth and a high suppression ratio of ~35 dB to reject out-of-band crosstalk [8]. The phase-correlated RZ signal is generated based on the optical Kerr shutter effect in a highly nonlinear fiber (HNLF). To the best of our knowledge, this is the first feasibility demonstration of 0.8-b/s/Hz spectral efficiency at 160-Gb/s rate without using polarization multiplexing scheme at a single wavelength.

II. PRINCIPLE OF OPERATION

The basic principle to generate a phase-correlated RZ signal is based on the optical Kerr shutter effect [9]. Similar techniques can be used to generate other phase-correlated signals such as CSRZ [10] and DPSK [11]. A Kerr shutter is an instrument that changes the transmittivity of a weak probe by an interaction with a strong pump in an isotropic nonlinear dielectric medium such as a fiber. Fig. 1 conceptually shows the nonlinear polarization rotation of the continuous-wave (CW) probe light due to cross-phase modulation induced by the pump. The pump and the probe are linearly polarized with an angle of 45° with respect to each other at the input of the fiber. At the output of the fiber, a polarizer blocks the probe in the absence of the pump, while the pump is rejected by a bandpass filter centered at the probe wavelength. When the pump is turned on, the phase shifts of the two orthogonal components of the probe become different due to the pump induced birefringence. The phase difference of the two orthogonal components determines the polarization and, therefore, the transmittivity of the probe after the fiber and

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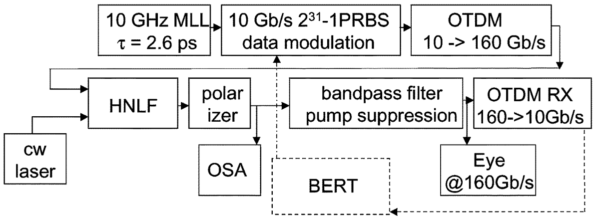

Fig. 2. Simplified schematic of the experimental setup.

the polarizer. Since the probe is CW and its transmittivity is determined by the pump intensity and independent of its phase, a phase-correlated RZ signal can be generated even with a noncoherent pump signal that stems from the OTDM processing.

For a phase-correlated RZ or NRZ signal, the two sidebands contain redundant information. VSB filtering can be applied to select one sideband by rejecting the other without losing the capability to recover the data. Such a technique was used in [5] to achieve a spectral efficiency of 0.64 b/s/Hz at 40 Gb/s with a single polarized signal. Here, we show the feasibility of achieving 0.8-b/s/Hz spectral efficiency at 160 Gb/s.

III. EXPERIMENTAL SETUP AND RESULTS

A simplified experimental setup is schematically shown in Fig. 2. A 10-GHz mode-locked fiber laser generates 2.6-ps (full-width at half-maximum) pulses, which are externally modulated with a pseudorandom bit sequence of $2^{31}-1$ word length. The wavelength of the pulses is 1546 nm. The RZ pulses are multiplexed by a four-stage OTDM multiplexer to form a 160-Gb/s pulse train. The 160-Gb/s OTDM RZ pulses are then launched into an HNLF as the pump pulses. A CW light at 1556 nm is injected into the HNLF as the probe. The HNLF has a length of 2.5 km, a Kerr nonlinearity efficient of 12/(Wkm), low polarization-mode dispersion, a zero dispersion wavelength at 1551 nm, and a dispersion slope of 0.02 ps/km/(nm)^2. The launched powers for the pump and the probe signals are ~18 and ~16 dBm, respectively. At the output of the HNLF, a polarization controller is used to adjust the polarization of the probe such that when the pump signal is switched OFF, the probe wave is blocked by the polarizer (less than −44-dBm measured power). After the polarizer, the pump is suppressed by a bandpass filter before the receiver. During the measurement, no specific stabilization of the HNLF was required. We kept the HNLF spoil in a box to protect it against airflow. Active readjustment of the transmitter was not required in a five-minute window. An optically preamplified OTDM receiver is used to detect the converted 160-Gb/s RZ probe signal. The first OTDM demultiplexing stage in the receiver configuration is similar to that in [12]. The receiver consists of an Er-doped fiber amplifier for preamplification, an electroabsorption modulator (EAM) with a low polarization dependency of <1 dB to demultiplex the 160-Gb/s signal to 40 Gb/s, and an electronic demultiplexer to further down convert the 40-Gb/s signal to 10 Gb/s for BER measurements. The EAM is driven at 40 GHz to provide a switching window of 3.5-ps width.

Fig. 3 shows the eye diagrams of the 160-Gb/s pump and the converted RZ signals, which were recorded with an optical sampling scope having a bandwidth over 500 GHz. Due to the nonlinear conversion process, the converted RZ signal possesses a shorter pulsewidth of 1.9 ps than the pump signal with a pulsewidth of 2.6 ps, as measured by an autocorrelator. The measured receiver sensitivities at a BER of 10^{-9} for the best and worst tributaries of the 160-Gb/s pump signal are −24.4 and −23.8 dBm, respectively. After the conversion, the sensitivities improve to −26.7 and −26.2 dBm for the phase-correlated RZ signal accordingly. This can be mainly attributed to the reduced pulsewidth and higher extinction ratio, as evidenced in Fig. 3.

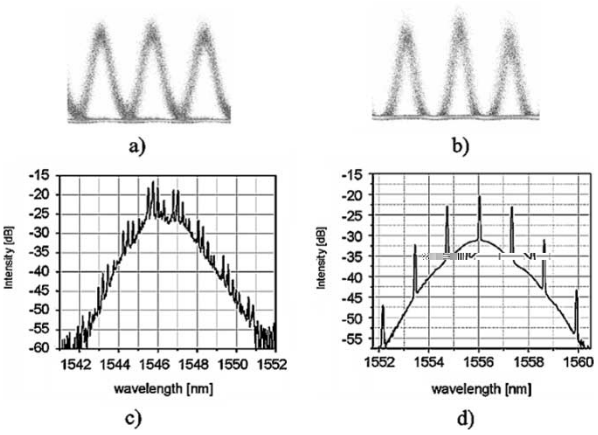

Fig. 3. (a) 160-Gb/s OTDM pump signal; (b) converted phase-correlated RZ signal; (c) and (d) are their corresponding spectra.

We further numerically and experimentally investigate the performance of the phase-correlated RZ signal in the presence of strong filtering [13]. We use a microelectromechanical-system-based blocker filter with a rectangular passband based on a design similar to that in [14]. This blocker filter possesses a good suppression ratio of ~35 dB with a square-like passband; therefore, we do not expect a severe penalty due to crosstalk in a WDM system. In addition, the square-like filter shape minimizes the required guard bands between WDM channels, the obtained results could be translated to a WDM system. The bandwidth of the filter can be tuned in a step of 13.2 GHz. The filter bandwidth is set to ~200 GHz. By simulation of the signal eye diagrams at different filter offsets, we found the optimum condition for VSB filtering. Best performance can be obtained when the filter offset is approximately 70 GHz. Fig. 4 shows a good agreement between the simulation and experimental results.

We also performed BER measurements at different filter offset conditions for both phase-correlated and phase-uncorrelated OTDM signals. Fig. 5 shows the spectra and Table I summarizes the results. As evidenced by the BER measurements, the random phase jumps between the adjacent bits in the filtered OTDM signal causes fluctuation in signal amplitude. Therefore, stable BER recording cannot be performed. The random phase jumps are drifting on a time scale of a second. This effect stems from the temperature- and vibration-caused length drift of the delay lines inside the OTDM unit. Error-free operation can be achieved when the filter offset is 70 GHz. Compared to the back-to-back sensitivity of ~−26 dBm, the large penalty of the filtered signal can be mainly attributed to four factors: the broadened pulsewidth, the intersymbol interference effects, the filter loss ripple (with a peak-to-peak value of ~2 dB), and nonideal receiver electronics. This penalty could be reduced to ~4 dB by using a better filter design to

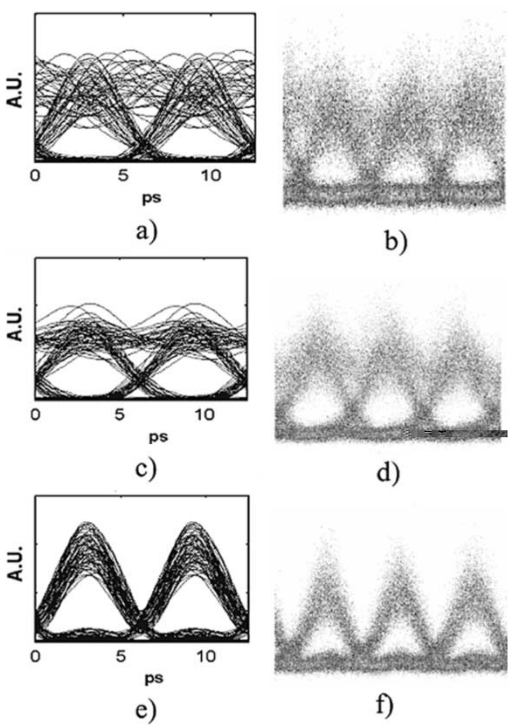

Fig. 4. (a) Simulated eye diagram with a filter bandwidth of 200 GHz and an offset of 0 GHz. (b) Measured eye diagram using an optical sampling scope. (c) and (d) Filter offset is 42 GHz. (e) and (f) Filter offset is 70 GHz. In the simulation, the filter is assumed to have a rectangular passband shape.

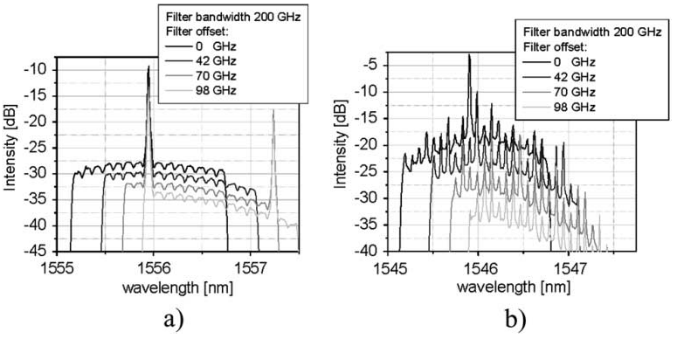

Fig. 5. Optical spectra of (a) phase-correlated signal, and (b) phase-uncorrelated OTDM signal, at different filter offsets of 0, 42, 70, and 98 GHz.

minimize the loss ripple. In addition, better BER performance could be achieved by employing forward-error-correction technique with a proper amount of overhead.

IV. CONCLUSION

We have demonstrated the feasibility of achieving a high spectral efficiency of 0.8 b/s/Hz at 160 Gb/s by using VSB filtering of phase-correlated RZ signal. With a filter bandwidth of 200 GHz, best performance is observed when the filter central frequency is offset by 70 GHz. Similar performance in a multichannel WDM system can be expected by using a rectangular-shaped filter like the one in the experiment. This result would be of interest for future high-capacity WDM systems operating at 160 Gb/s with a high spectral efficiency of 0.8 b/s/Hz.

TABLE I
PERFORMANCE OF THE VSB-RZ AT DIFFERENT FILTER OFFSETS

Sensitivities or BERs		0 GHz	42 GHz	70 GHz	98 GHz
Phase-correlated RZ	Best tributary	10^{-8}	10^{-6}	-17.2 dBm	10^{-5}
	Worst tributary	10^{-7}	10^{-4}	-13.9 dBm	10^{-5}
OTDM RZ		NA	NA	Drifts between 10^{-5} and 10^{-8}	NA

Sensitivities are measured at BER = 10^{-9}
NA: stable BER measurements cannot be performed

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