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Simultaneous Demodulation and Clock-Recovery of 40-Gb/s NRZ-DPSK Signals Using a Multiwavelength Gaussian Filter

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Abstract—We demonstrate a novel optical circuit that has the potential of simultaneous demodulation and all-optical clock-recovery of 40-Gb/s wavelength-division-multiplexing nonreturn-to-zero differential phase-shift keying (NRZ-DPSK) signals. A key device of the circuit is an ad hoc periodic fiber Bragg grating filter that simultaneously demodulates the input signals and seeds a series of clock recovery circuits. We report the complete characterization of the proposed scheme in the whole *C*-band using a tunable transmitter. The DPSK demodulated signals show enhanced resilience to chromatic dispersion with respect to the usual NRZ ON-OFF keying format. On the other hand, the recovered clock signals are very stable and have around 200-fs root-mean-square time jitter.

Index Terms—All-optical clock recovery, phase modulated format, semiconductor optical amplifier (SOA).

I. INTRODUCTION

IN THE past few years, phase modulation formats such as differential phase-shift keying (DPSK) acquired increasing popularity thanks to their higher resilience to nonlinear impairments and better optical signal-to-noise ratio (OSNR) sensitivity than the usual ON-OFF keying (OOK) format if asymmetric Mach-Zehnder interferometers (MZIs) and balanced detection are used [1]. An alternative demodulation scheme to the MZI based on proper signal filtering was theoretically proposed in [2]. We recently reported that 10-Gb/s nonreturn-to-zero (NRZ)-DPSK signals can also be demodulated using a Gaussian-shaped optical filter having bandwidth of around 60% of the bit rate [3]. When using this demodulation scheme, we actually obtain an optical duobinary-like or CAPS code modulation format, largely increasing the signal tolerance to chromatic dispersion [2]–[4]. To accomplish filtering demodulation, we used a fiber Bragg grating (FBG) filter in reflection centered at the carrier wavelength. Furthermore, the light passed through the FBG can be effectively exploited for all-optical clock recovery (CR) [5]. All-optical CR circuits are supposed to play a critical role in future high-speed all-optical networks. Indeed stable and low-jitter synchronization signals will be required in several network subsystems as receivers, regenerators, etc. [6]. Regarding phase modulated formats, while

Fig. 1. Experimental setup. TL: Tunable laser. PC: Polarization controller. OI: Optical isolator. BPF: Bandpass filter. Insets: (a) example of a demodulated DPSK signal; (b) recovered clock trace. Bottom: periodic FBG filter spectrum and the comparison of the real filter shape and a Gaussian curve at a sample channel.

CR from return-to-zero (RZ)-DPSK signals can be performed by usual techniques, NRZ-DPSK signals have almost constant intensity and in principle no carrier nor clock lines in the signal spectrum. However, in practical realizations, weak clock spectral components are present, making the CR possible but still a harder task. In this letter, we demonstrate a single optical receiver circuit able to simultaneously demodulate 40-Gb/s wavelength-division-multiplexing (WDM) NRZ-DPSK signals in the whole *C*-band and, also perform CR on each channel. We characterize the back-to-back sensitivity of the demodulated signals and measure their chromatic dispersion resilience (in comparison with common NRZ-OOK signals). On the other hand, we show that the recovered clock signals have ultralow jitter and high stability, suitable for a number of synchronization applications.

II. EXPERIMENT AND DISCUSSION

The experimental setup is reported in Fig. 1. In order to characterize the circuit, we used one tunable transmitter instead of a full set of WDM channels. This is not clearly a limitation. Tuning the transmitter wavelength and optimizing according to the CR circuit, we measured the multiwavelength performance of the scheme in the overall *C*-band. The DPSK transmitter was made by a tunable laser modulated by a LiNbO₃ modulator at 39.97 Gb/s (the bit-rate being determined by the FPF in the CR

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Fig. 2. (a) OSNR sensitivity of narrow filtered 40-Gb/s NRZ-DPSK signals for sample C-band channels (sensitivity of NRZ-OOK is reported for comparison), on the right BER measurement for one of the channels. (b) Comparison of the OSNR penalty versus chromatic dispersion for the two modulation formats for the channel at $\lambda = 1550.8$ nm. Eye diagrams evolution is reported in the insets.

circuit) with a pseudorandom binary sequence (PRBS) (no differential encoding was required). At the DPSK transmitter, we tested both a pure phase modulator and an intensity modulator biased at the maximum of the transfer function. The results in the following are obtained using the intensity modulator. When using the phase modulator, we found very similar results for the CR but worst results for the demodulation sensitivity. This was due the bandwidth limitation of the phase modulator for this particular demodulation technique [7]. The signal was then amplified by an erbium-doped fiber amplifier to account for circuit losses and sent via an optical circulator (OC) to the periodic filter. This is the key component in the scheme. It has a twofold action. In reflection, it is capable to simultaneously demodulate 100-GHz-spaced 40-Gb/s WDM-DPSK channels. At the same time, in transmission it feeds with RZ-like data a number of parallel RZ-CR circuits. It was custom-made by Teraxion and had a 100-GHz channel periodicity in all the C-band, around 24-GHz bandwidth (60% of the bit rate) for each channel and an almost Gaussian profile with low group delay to avoid spurious dispersion (see the filter spectrum in Fig. 1). Combined with the OC and an arrayed waveguide grating (AWG), the periodic filter provides effective DPSK demodulation for all the reflected WDM NRZ-DPSK channels [see Fig. 1(a)] [3]. It works selecting the part of the signal spectrum corresponding to phase persistences while rejecting the phase transitions, which leads to phase-to-intensity conversion [2]–[4]. The OSNR sensitivity at 10^{-9} bit-error rate (BER) for a number of sample wavelengths in the C-band with a $2^{23} - 1$ PRBS sequence is reported in Fig. 2(a). Moreover, as can be seen from the BER measurement (at $\lambda = 1550.8$ nm), reported for example in Fig. 2(a), we found no evidence of any BER floor. We indicate for comparison the NRZ-OOK sensitivity obtained for the same preamplified re-

ceiver. In respect to this value, we measured an OSNR penalty ranging from 1.5 to 3.7 dB. Part of this penalty (~ 1.5 dB) is known to come from the narrow filtering technique [4]. All the measurements at this point are made using a common electrical CR circuit. The additional penalty comes from slight filter bandwidth and shape inhomogeneities (e.g., filter bandwidth slightly increase at longer wavelengths from 24 to 28 GHz). However, despite this back-to-back OSNR penalty, the signals show a significantly larger resilience to chromatic dispersion compared to both conventional OOK and usual DPSK demodulated by the conventional one-bit delay interferometer [2]–[4]. Using different spools of fiber, we analyzed the resilience to chromatic dispersion of the narrow-filtered DPSK compared to the usual NRZ-OOK. The result (for a channel at $\lambda = 1550.8$ nm) in terms of OSNR penalties with respect to the NRZ-OOK sensitivity versus total chromatic dispersion is reported in Fig. 2(b) (in the insets we show some of the corresponding eye diagrams).

We found that the back-to-back OSNR penalty was cancelled for 50 ps/nm of accumulated chromatic dispersion and the filtered DPSK sensitivity acquired a 3.8-dB advantage at 100 ps/nm. The BER performance for this modulation format was then almost constant up to 150-ps/nm total dispersion. We see from the insets the evolution of the eye diagrams showing eye opening in propagation as expected from [4]. Penalty starts to increase at 200 ps/nm. The tolerance to chromatic dispersion (considering 3-dB OSNR penalty) is increased by a factor of around 2.5. A higher improvement was obtained at 10 Gb/s [3], and was theoretically expected for an optimum filter. This difference is likely due to the practical filter implementation. On the other hand, each channel that passes through the FBG experiences notch filtering, which selects the phase transitions of the incoming NRZ-DPSK data. This results in a signal having a pulse corresponding to each phase transition. This RZ-like signal is suitable to feed a usual CR. Here we used an AWG to separate the channels and a simple CR based on a 40-GHz Fabry-Pérot filter (FPF) followed by a power limiting stage [5]. In Fig. 3, we report the evolution of the optical spectrum and of the signal trace in the CR circuit for the channel at $\lambda = 1546.8$ nm and using a $2^9 - 1$ PRBS sequence. In this case, the length of the PRBS sequence ($2^9 - 1$) was limited by the finesse (F) of the available FPF in the CR. Indeed, when longer sequences were used, residual pattern oscillation led to clock degradation in a way similar to [5].

For these longer sequences, a higher Finesse is required or, however, once the RZ-like signal is obtained from the FBG pre-processing, any other usual CR circuit can be used as an alternative. In Fig. 3(a), we reported the signal after the FBG (very similar to an RZ signal). This RZ-like signal then passed into the fiber-based FPF (4-dB insertion loss, 39.97-GHz free spectral range and an $F = 270$, corresponding to a bandwidth of around 150 MHz). Because of a slight polarization dependence of the component, a polarization controller was used to maximize the filter output. This can be clearly removed if using a polarization-independent filter. The FPF selected the spectral clock lines removing most of the incoming modulation. This produced a pulse train as shown in Fig. 3(b). However, due to the limited memory effect of the FPF, a certain amount of amplitude oscillations related to the incoming pattern sequence was present. This

Fig. 3. Evolution of the optical spectra and scope traces in the CR circuit. (a) After the FBG; (b) after the FPF; (c) after the output BPF. OSA resolution bandwidth = 0.01 nm.

residual intensity modulation was largely attenuated exploiting the frequency high-pass filtering properties of a saturated semiconductor optical amplifier (SOA) [8]. To this aim, we used a polarization-insensitive pigtailed SOA with 28-dB small signal gain and 6-dBm output saturation power at 200-mA driving current. An optical isolator was used to reduce spurious reflections. The optical power level at the SOA input was around 0 dBm corresponding to 22-dB gain compression. The interplay of non-linear and saturation effects in the SOA and the use of a 1-nm bandpass filter that selects part of the output optical spectrum completely reformatted the clock waveform to a low amplitude jitter signal [see Fig. 3(c)] [8]. We measured the root-mean-square (rms) time jitter of the recovered clock with the ultra-stable time reference module of the sampling oscilloscope *Agilent 86100* (minimum rms jitter resolution ~ 200 fs) using a number of different signal wavelengths spanning the *C*-band. The results are reported in Fig. 4(a). All the values were very close to the limit of the scope and resulted in the range 180 to 230 fs, showing the multiwavelength operation of the scheme.

A screenshot of the recovered clock recorded at the sampling oscilloscope during the time jitter measurement is reported as an example in Fig. 4(b). The locking range of the CR was 150 MHz, being related to the bandwidth of the FPF. Finally, the stability

Fig. 4. Jitter measurements. (a) RMS time jitter for a number of sample wavelengths in the *C*-band; (b) screenshot of a jitter measurement.

of the recovered clock was proved using it to synchronize the error detector during BER measurements. We measured no variations in the BER curves comparing our optical CR with an electrical one similarly to what was found in [5] having the same sensitivity values as reported in Fig. 2(a).

III. CONCLUSION

We demonstrated 40-Gb/s operation of an optical circuit for the simultaneous demodulation and clock recovery of NRZ-DPSK signals. We exploited a custom periodic FBG filter to obtain multiwavelength demodulation and CR seeding in the whole *C*-band. The demodulation is not interferometric with balanced detection, therefore, we miss the theoretical 3-dB advantage in back-to-back sensitivity but obtain enhanced tolerance to chromatic dispersion with the use of a simpler and stable structure. On the other hand, the recovered clock signals are very stable and have low rms time jitter (~ 200 fs). We used a tunable transmitter to emulate multiwavelength operation and demonstrated the potential of the scheme for WDM operation.

REFERENCES

- [1] A. H. Gnauck and P. J. Winzer, "Optical phase-shift-keyed transmission," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 115–130, Jan. 2005.
- [2] A. Røyset and D. R. Hjellme, "Novel dispersion tolerant optical duobinary transmitter using phase modulator and Bragg grating filter," in *Proc. ECOC98*, 1998, pp. 225–226.
- [3] A. D'Errico *et al.*, "WDM-DPSK detection by means of frequency-periodic Gaussian filtering," *Electron. Lett.*, vol. 42, no. 2, pp. 112–114, Jan. 2006.
- [4] E. Forestieri and G. Prati, "Narrow filtered DPSK implements order-1 CAPS optical line coding," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 662–664, Feb. 2004.
- [5] G. Contestabile, M. Presi, N. Calabretta, and E. Ciaramella, "All-Optical clock recovery for NRZ-DPSK signals," *IEEE Photon. Technol. Lett.*, vol. 18, no. 23, pp. 2544–2546, Dec. 1, 2006.
- [6] S. Bigo, O. Leclerc, and E. Desurvire, "All-optical fiber signal processing and regeneration for soliton communications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 3, no. 5, pp. 1208–1223, Oct. 1997.
- [7] P. Boffi *et al.*, "Impact of the electro-optical modulator on CAPS code dispersion tolerance," in *2007 Eur. Conf. Lasers Electro-Optics Int. Quantum Electron. Conf.*, Munich, Germany, Jun. 2007, pp. 1–1.
- [8] G. Contestabile *et al.*, "A simple and low-power optical limiter for multi-GHz pulse trains," *Opt. Express*, vol. 15, pp. 9849–9858, 2007.