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Investigation of multiwavelength clock recovery based on heterodyne beats of sideband-filtered signal

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Abstract

We investigate a new parallel all-optical clock recovery scheme based on heterodyne beats of an optical sideband-filtered signal. The oscillating clock signal is recovered when the filtered sideband is combined with a stable local oscillator. The filtering is performed with an optical resonator, which by nature provides possibility for multiwavelength operation. The local oscillator could be realized by a multiwavelength laser, whose emission wavelengths are injection seeded with carrier wavelengths of the input data. The output signal of such a configuration benefits from a reduced bit-pattern effect and a stable offset level. The sideband filtering is demonstrated for 23 simultaneous channels at 100 GHz DWDM grid, each hosting a data stream of 10 Gbit/s.

Keywords: Optical communications; Parallel processing; All-optical devices; Resonators

1. Introduction

Clock recovery (CR) is a common operation found in optical telecommunication systems, where the receiver acquires information about the transmitter clock from the incoming flow of bits. In optical CR the timing is resolved partly or fully in the optical domain. Optical CR has been performed, e.g., by use of optical phase locked loops [1], multisection laser diodes [2,3], Brillouin scattering [4,5], electro-absorption modulators [6], optoelectronic oscillators [7], and Fabry-Perot filters (FPF) [8–10]. A vast majority of the studies have been performed for single wavelength systems, whereas multiwavelength operation has been demonstrated only a few times. These multiwavelength CR schemes resolve typically two to four wavelength channels for one single data rate at a time [5,11,12]. Optical resonators are passive elements having periodic wavelength dependence in transmission, and therefore, they are inherently suitable for multiwavelength optical CR. However, they suffer from a bit-pattern effect, i.e., the intensity of the recovered clock pulses depends on the input signal bit pattern. Several methods for reducing the input bit pattern dependence have been proposed, such as use of a variety of self-pulsating laser sources [2,3,13]. These methods serve well in synchronous networks, where the incoming data arrives at narrowly defined time windows. In asynchronous networks the laser-based schemes may, however, be problematic, because successive data packets are not necessarily synchronized with each other. In other words, a data packet may have a half-bit phase shift when compared to the preceding packet. For a self-pulsating CR device this implies a need for long lock-in times. In order to have low network latency one benefits from short lock-in time, while keeping the bit-pattern effect limited. A promising candidate for all-optical CR under these conditions is FPF assisted SOA processing [10,14], which is limited for single wavelength operation

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due to SOA nonlinear properties. For multiwavelength operation in an asynchronous network one would desire a linear resonator-based method, yet, with reduced bit-pattern effect. An additional challenge of optical resonator based CR is the narrow passband of a high finesse resonator, which leads to the requirement that the carrier wavelengths must accurately match the transmission peaks [15].

In this paper, we propose a new resonator based multiwavelength all-optical CR technique. The technique is a combination of a traditional resonator and an injection-seeded laser based CR methods. It inherits the benefits of the conventional resonator based method, such as the short lock-in time and the possibility for multiwavelength operation, but as an improvement to conventional resonator based CR it provides the possibility for (i) reduced bit-pattern effect and (ii) a wider bandwidth. Furthermore, the resonator free-spectral range (FSR) may be matched to a WDM channel grid instead of the data rate of the signal. In our demonstration, we show beats of an optical sideband filtering at 23 simultaneous WDM channels operating at 10 Gbit/s data rate.

2. Principle

The optical frequency spectrum of a return-to-zero (RZ) modulated signal contains amplitude maxima at carrier and sideband frequencies (see Fig. 1). A Fabry-Perot filter (FPF) is used to extract the sideband frequency, which serves as a signal oscillator (SO) in our heterodyne setup. The SO is combined with a stable local oscillator (LO) operating at the carrier frequency, which results in a beating output signal; its frequency being proportional to the data rate. The method resembles the conventional resonator based CR, except that the intensity of the signal at the carrier frequency (LO) remains constant and does not vary with the input signal bit pattern. This seemingly small dissimilarity leads to two substantial differences: (1) The offset level of the sideband-filtered signal does not vary, and (2) the decay time of the sideband-filtered beat is twice the photon lifetime of the resonator. These characteristics are evident in Fig. 2, which depicts a simulated response of a pseudorandom 100 Gbit/s RZ modulated signal for (a) a conventional and (b) a sideband filtered heterodyne setup. The setup with the heterodyne beats maintains the amplitude of the oscillation longer than the conventional setup and keeps a stable signal offset regardless of the input signal pattern. The simulation assumes a resonator photon lifetime of 31.6 ps, which implies resonator FWHM (full width at half-maximum) bandwidth of 5 GHz, a typical bandwidth tolerance in current lightwave systems. In addition, the proposed method is suitable for multiwavelength operation, because the resonator FSR does not have to match the data rate, but just the channel spacing. Therefore, it is possible to filter, e.g., 100 Gbit/s signals channel-by-channel by using standard resonators with an FSR of 400 or 500 GHz according to the WDM channel grid utilized.

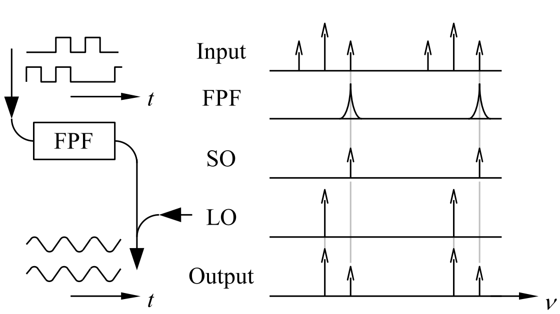

Fig. 1. Multiwavelength clock recovery with optical sideband filtering and heterodyne beating. Abbreviations: FPF – Fabry-Perot filter; SO – signal oscillator; LO – local oscillator.

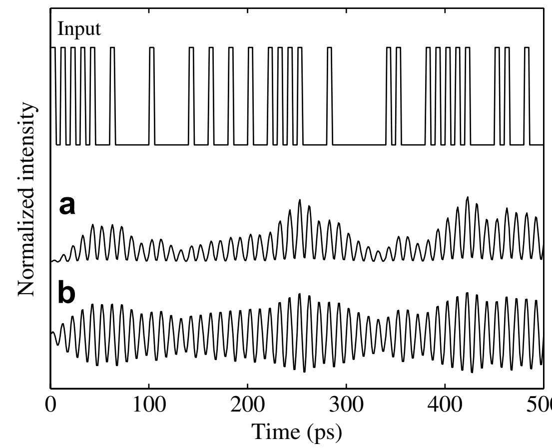

Fig. 2. Simulation of (a) conventional FPF filtering and (b) heterodyne beats of sideband-filtered signal. Simulated RZ modulated data rate is 100 Gbit/s, and photon lifetime of the resonator is 31.6 ps (FWHM bandwidth of 5 GHz). The simulation begins with a start-up sequence of five digital ones.

The photon lifetime τ of a resonator is defined as the time the intra-cavity intensity decays to $1/e$ value of the initial intensity level, i.e., $I = I_0\exp(-t/\tau)$. For the intra-cavity electric field, the exponential time evolution may naturally be written as $\exp(-t/2\tau)$. The doubling of the time constant in case of the sideband filtered heterodyne beat can be shown by writing the LO and SO electric fields as

$$E_{\mathrm{LO}} = E_{0,\mathrm{LO}} \exp(\mathrm{j}\,2\pi \nu_0 t) \tag{1}$$

and

$$E_{\mathrm{SO}} = E_{0,\mathrm{SO}} \exp(-t/2\tau) \exp(\mathrm{j}\,2\pi \nu_1 t), \tag{2}$$

where t is the time, τ is the photon lifetime of the resonator, and ν_0 and ν_1 are frequencies of the carrier and sideband, respectively. The output intensity is proportional to $(E_{\mathrm{LO}} + E_{\mathrm{SO}})(E_{\mathrm{LO}} + E_{\mathrm{SO}})^*$, which simplifies to

$$I \propto I_{0,\mathrm{LO}} + 2E_{0,\mathrm{LO}}E_{0,\mathrm{SO}} \exp(-t/2\tau) \cos[2\pi(\nu_0 - \nu_1)t], \tag{3}$$

when $E_{0,\mathrm{SO}} < E_{0,\mathrm{LO}}$. The prolonged decay $\exp(-t/2\tau)$ is beneficial in a sense that for a desired number of digital zero bits to be recovered the resonator bandwidth may be selected twice as wide compared to conventional set-ups. In addition, the stable offset level benefits decision-making

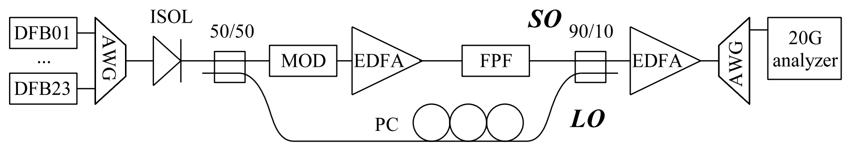

Fig. 3. Experimental setup. Abbreviations: DFB – distributed feedback laser; AWG – arrayed waveguide grating; ISOL – isolator; 50/50 – fiber coupler; MOD – modulation (including RZ pulse shaping and data modulation (see text); EDFA – erbium doped fiber amplifier; FPF – Fabry-Perot filter; PC – polarization controller; SO – signal oscillator; LO – local oscillator; 90/10 – fiber coupler.

process, where the threshold level may be set slightly above the CW offset. As presented in Fig. 2 one can easily find an adequate decision threshold for the sideband-filtered signal (b), which is not the case with the conventional resonator CR output signal (a).

An important part of the proposed CR scheme is the multiwavelength LO, which should not suffer much from bit-pattern effects and should track the carrier frequencies of the processed channels. An LO with these properties may be obtained by constructing a multiwavelength emitter, which is injection seeded with the carrier wavelengths of the input data. For the multiwavelength lasing one may choose, e.g., an EDFA or an LOA based design [16,17]. The carrier wavelengths for the LO injection may be extracted with a periodic broadband filter.

In a recent work, we used a setup utilizing a simple resonator, instead of an injection seeded laser, and demonstrated CR for 21 simultaneous wavelength channels at two different data rates [18]. An obvious benefit of such a setup is the inherent simplicity, yet, the drawback is the temporal evolution of the LO amplitude, which is reflected in a bit-pattern effect, a narrower transmission bandwidth, and a varying offset level.

In the following, we demonstrate the predicted photon lifetime doubling and multiwavelength operation of our sideband filtering approach for 23 simultaneous wavelength channels at a 100 GHz DWDM grid, with all the channels operating at a data rate of 10 Gbit/s.

3. Experiments

The experimental setup is shown in Fig. 3. It comprises a set of DFB lasers, whose outputs are combined with an arrayed waveguide grating (AWG) with an ITU specified equidistant frequency spacing of 100 GHz. The combined output is fed through an isolator and split into two arms. One arm is modulated with a 10-Gbit/s PRBS RZ sequence and the other arm is left intact thus serving as the LO. The RZ signal is generated in a common way (see, for example, approach "RZ 12.5" in [19]) by a pair of identical Mach–Zehnder modulators, both with a 3-dB bandwidth of 15 GHz and biased at $V_\pi/2$ (2.9 V). One of the modulators, in our case the first one, is driven with a sinusoidal signal of amplitude $V_\pi/2$ (which means the peak-to-peak voltage swing equals $V_\pi = 5.8$ V) with a frequency matching the data rate (here: 10 GHz) in order to achieve the RZ pulse shaping. The pulse width (full width at half maximum, FWHM) was measured to be ΔT_{FWHM} ≈40 ps. At this point (periodic pulse stream) the optical spectrum consists of sharp lines centered around the carrier frequency with 10 GHz spacing. The second modulator accomplishes the data modulation, which means it is driven by 10 Gbit/s NRZ 2^7–1 PRBS signal (V_π voltage swing peak-to-peak). The modulated signal is amplified with an EDFA and launched into the FPF for sideband filtering. The FPF is a 2 mm long piece of single-mode fiber with reflective coatings on the end-facets (FSR = 50 GHz, FWHM of the optical passband, i.e., bandwidth BW = 1.32 GHz). The filtered signal, i.e. the SO, is combined with the LO using a fiber coupler with a split ratio of 90/10. The combined signal is amplified further and the DWDM channels are separated with an AWG.

The output is analyzed, channel-by-channel, with a fast oscilloscope. As is typical for heterodyne setups, the coherence of the LO should be as high as possible. Fluctuations of the phase between the SO and the LO signal cause drift in the beat. The output signal was found to confirm the predictions of a stable offset level and the decay time, which was twice the photon lifetime of the resonator (see Fig. 4). Fig. 5 shows the signals recorded from 23 channels. The signals were averaged ($n = 4$) in order to improve the signal-to-noise level.

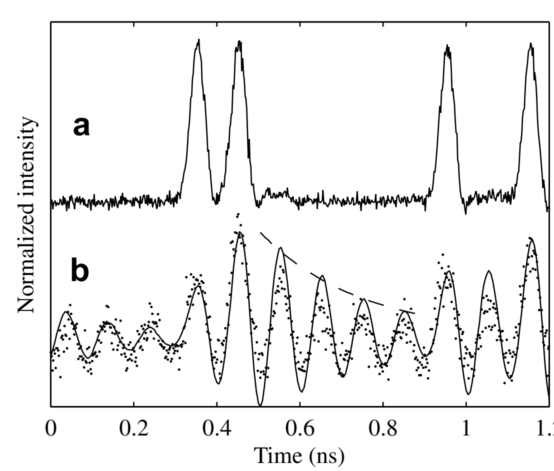

Fig. 4. (a) Input signal and (b) sideband-filtered heterodyne beat. The simulated response (continuous line) follows closely the recorded output (dots). Signal decay envelope (dashed line) has twofold time constant (240 ps) compared to the resonator photon lifetime (120 ps).

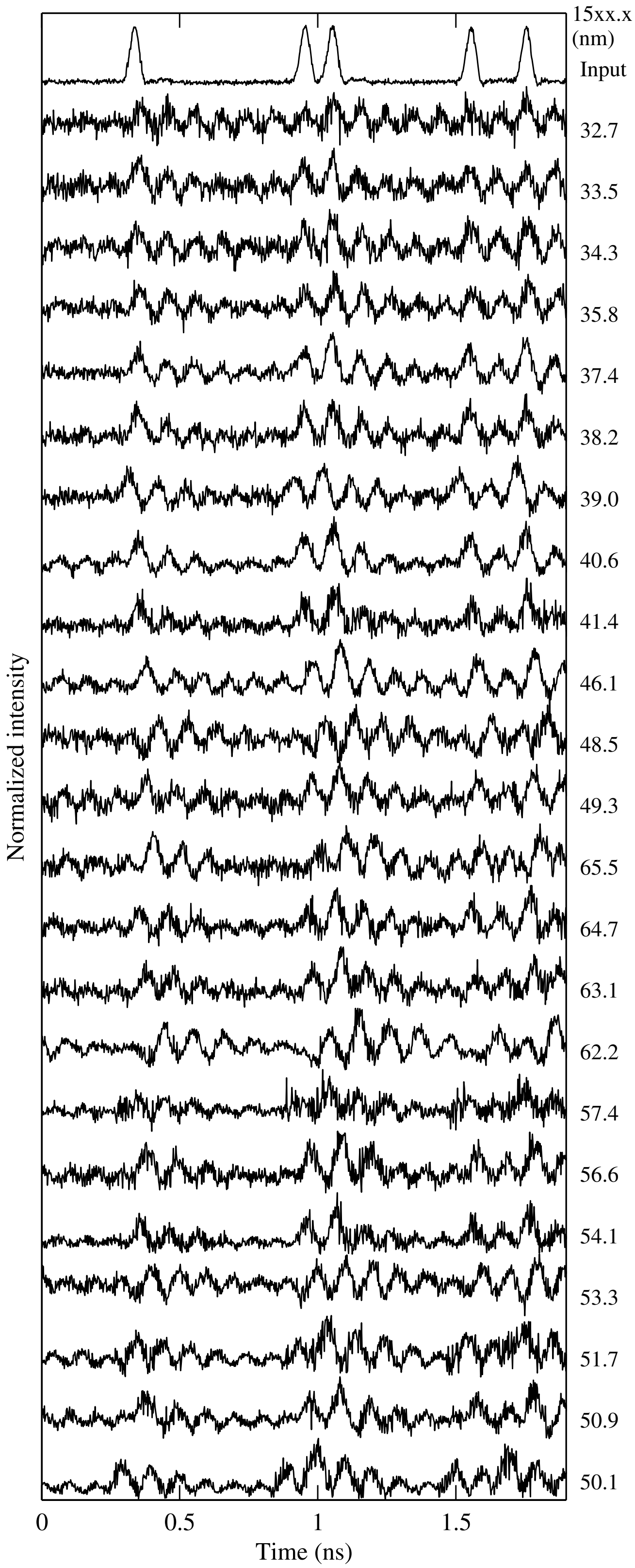

Fig. 5. Outputs of the different channels.

4. Conclusions

We have proposed and investigated an all-optical clock recovery scheme based on heterodyne beats of a sideband-filtered signal. The approach enables multiwavelength operation when the resonator FSR conforms to the ITU DWDM grid, while being independent of the data rate of the signal. The simulated response shows greater signal offset stability than conventional resonator based CR. The heterodyne beats by sideband filtering were demonstrated for 23 simultaneous DWDM channels. The analysis of the proposed scheme predicts that the beat decay is by a factor of two greater than the resonator photon lifetime, which agrees with the measurements. The prolonged decay of the beat in presence of multiple zeros permits the use of resonators with lower finesse. In addition, the output signal oscillates around a stable offset level, which is potentially helpful for decision-making process. The method requires a local light source with adequate coherence properties.

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