Multichannel and Rate All-Optical Clock Recovery

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Abstract—We report on a new clock recovery scheme utilizing a birefringent fiber resonator and a polarizer that allows for parallel all-optical processing of multiple channels and rates. It is demonstrated for 21 simultaneous channels, 20 carrying data at 10 Gb/s and one at 40 Gb/s. Earlier demonstrations of multichannel operation have reported four recovered channels at only one single rate.

Index Terms—All-optical clock recovery (CR), birefringence, Fabry–Pérot resonators, wavelength-division multiplexing.

I. INTRODUCTION

CLOCK recovery (CR) is a fundamental operation in all digital transmission systems, including optical telecommunications. Today it is performed in the electrical domain, but in recent years considerable effort has been made to find optical alternatives, including the use of electrooptical phase-locked loops [1], multisection laser diodes [2], fiber ring lasers [3], Brillouin scattering [4], two-photon absorption [5], and spectral filtering using Fabry–Pérot resonators [6]–[8]. These methods have been proven substantially faster than available electrical ones. However, most of these schemes work only for one wavelength channel at a time and demonstrations of parallel operation have remained few. Since the optical fiber in a dense wavelength-division-multiplexing (DWDM) system hosts multiple wavelength channels, it is desirable to extend this parallelism to signal processing by finding means of all-optical CR. This type of approach has been demonstrated for two [4], [9], and four [10], simultaneous wavelength channels for a single data rate.

In this letter, we propose a new all-optical CR scheme based on a simple device consisting of a birefringent resonator and a polarizer. We demonstrate the concept for 21 simultaneous channels, 20 carrying data at 10 Gb/s and one at 40 Gb/s. To the best of our knowledge, in terms of channel count this is five times more than current state-of-the-art and this is also the first reported demonstration of simultaneous multirate processing. The scheme is fully passive and could be extended over the entire C- and L-bands, bringing the number of processed channels up to 100 or more. This must be contrasted with most other proposed optical CR methods, which practically or theoretically are limited to less than ten channels.

II. PRINCIPLE OF OPERATION

The combination of a birefringent resonator and a polarizer has been shown to generate mode beats at frequency $f = c\Delta n/(\lambda_0 n)$, where c is the speed of light and λ_0 the wavelength in vacuum, Δn is the difference of refractive indexes of the polarization modes, and n is the average index of refraction ($\Delta n \ll n$) [11]. It is worth noting that the beat frequency is proportional to the degree of birefringence, and does not depend on the resonator length. Earlier CR methods based on Fabry–Pérot resonators require a match between the resonator length ℓ and the data rate B [6], [12] of the modulated signal: $\ell = c/(2nB)$. The transmission comb of the resonator must also coincide with the carrier wavelength λ_0 of the modulated signal: $\ell = m_1\lambda_0/2$, where m_1 is an integer. When employing multiwavelength CR with a simple Fabry–Pérot resonator, the channel spacing Δf should be a multiple of the resonator's free-spectral range (FSR): $\Delta f = m_2 c/(2n\ell)$, where m_2 is an integer. In other words, one parameter, namely the resonator length ℓ, has to fulfill three independent requirements concerning 1) the data rate, 2) the carrier wavelength, and 3) the channel spacing. This difficulty possibly explains why demonstrations of multiwavelength CR by use of conventional Fabry–Pérot resonators have not emerged. In our scheme, the match between the resonator length and the data rate is not required. This permits the resonator FSR to be matched to the channel grid, while the data rate is determined by the degree of birefringence: $B = f = c\Delta n/(\lambda_0 n)$.

The generation of mode beats can be understood by perceiving the birefringent resonator as a pair of independent resonators oriented orthogonally to each other with two individual transmission combs [Fig. 1(d)]. The light launched into the resonator should be oriented so that it excites both polarization modes. The scheme can be made polarization-insensitive by using a circulator and a polarizing beam splitter [10], [13]. In case of return-to-zero (RZ)-modulated input [Fig. 1(a)], the carrier wavelength and the transmission peak of one resonator are tuned to match, and the transmission peak of the other resonator is tuned to one of the first sidebands [Fig. 1(b)]. When the polarizer selects optical power from both polarization modes, a beating signal [Fig. 1(c)] is generated, with a beat frequency proportional to the frequency difference of the transmission peaks, i.e., proportional to the birefringence of the resonator. Other possible spectral components filtered by the setup are nonmeaningful, provided their optical power remains low enough compared to the power of the carrier and the selected sideband.

The proposed approach enables CR at multiple channels and data rates. For example, if the FSR is 50 GHz and the separation of spectral signal components is 10 GHz, the clock may be recovered for 10, 40, and 160 Gb/s, among others, since one finds these
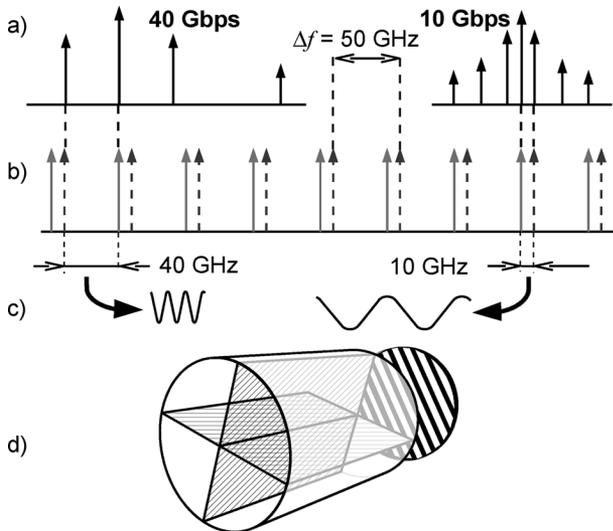
Fig. 1.   Operation principle of passive all-optical CR using a birefringent fiber resonator. (a) Spectral decomposition of input signal at 40 and 10 Gb/s. (b) Suitably tuned birefringent resonator may filter both clock signals simultaneously. (c) Suitably polarized output signal beats at the clock frequency. (d) The CR device consisting of a birefringent resonator and a polarizer.

frequency differences in the resonator dual transmission spectrum. These particular values are convenient, since both the frequency spacing within the channel grid defined as multiples of 50 GHz as well as the data rates of 10, 40, and 160 Gb/s are widely used. In real optical transmission systems, the data rates are typically not exact integer multiples of 10 Gb/s, yet the CR with the method described may still be performed, provided that the filtered spectral features are within the passbands of the resonator.

The number of recoverable channels is dependent on the resonator bandwidth and the FSR difference of the polarization modes. For 10-GHz detuning the birefringence Δn will be 7.6×10^{-5}, which translates in FSR difference of 2.6 MHz. For a resonator with the transmission bandwidth of 600 MHz, this would mean about 200 recoverable channels.

III. EXPERIMENTAL SETUP AND RESULTS

Our experimental setup (see Fig. 2) contains 20 distributed feedback (DFB) lasers and one 40-GHz mode-locked laser (MLL), which are $2^7 - 1$ pseudorandom binary sequence (PRBS) RZ modulated for SDH/SONET data rates of 9.953 28 and 39.813 12 Gb/s, respectively. All the light sources operate within the C-band at the ITU specified channel wavelengths with an equidistant spacing of 100 GHz. The amplified data are combined and launched into the birefringent resonator, which is a 2-mm-long piece of standard single-mode fiber concealed in a glass ferrule [FSR = 49.9 GHz, BW = 645 MHz (full-width at half-maximum)]. The pigtailed resonator was placed in a clamp, which induced lateral force and thus birefringence. The birefringence, i.e., the separation of the transmission maxima, was tuned using a separate setup having a broadband light source and an optical spectrum analyzer. The stress of the clamp was gradually increased, until the separation of the peak maxima reached 10 GHz. The output signal was polarized and then acquired using a digital communication analyzer and a fast sampling oscilloscope for the 10- and 40-GHz signals, respectively. The wavelengths of the 10-Gb/s channels were
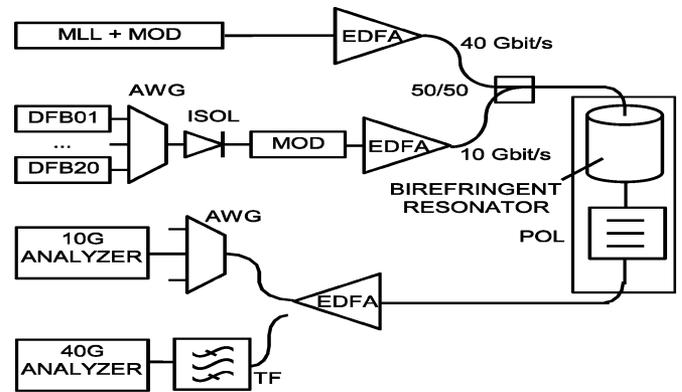

Fig. 2.   Experimental setup. Abbreviations: MLL + MOD—MLL with RZ modulated 40 Gb/s PRBS data stream; ISOL—optical isolator; MOD—modulator; POL—polarizer, TF—tunable optical bandpass filter.
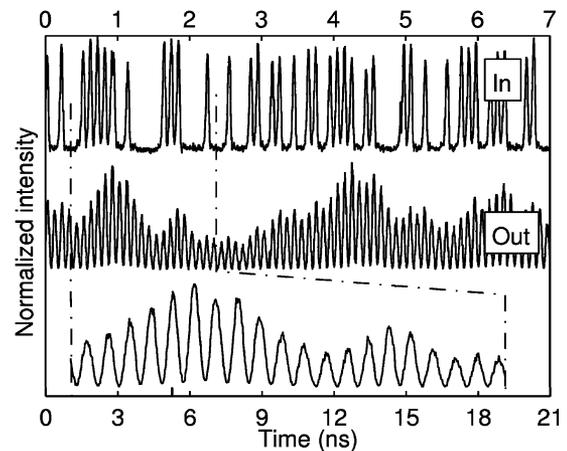

Fig. 3.   Signals of the CR setup. In: input signal consisting ones and zeros. Out: output from one channel. Below: magnified portion of the signal.

optimized with respect to the resonator passbands before recording the data. The optical amplified spontaneous emission noise was filtered out by an arrayed waveguide grating (AWG) or a tunable bandpass filter.

When all 10- and 40-Gb/s channels were properly adjusted, data were acquired channel-by-channel. Since the resonator had no active temperature control, the transmission combs were drifting slowly. Therefore, minor adjustment (wavelength tuning of a few picometers) was made for most channels prior to the data recording. For the 40-Gb/s channel, the output was switched from the AWG to a tunable filter in order to accommodate the broader signal spectrum. A general observation was the increase of noise as channels were added, which can be explained by reduction of gain for individual channels due to the erbium-doped fiber amplifier (EDFA) output power saturation.

The input signal and the corresponding output signal from one 10-Gb/s channel are depicted in Fig. 3. The output exhibits typical response of a resonator, where the output beat amplitude varies according to the input signal pattern [12]. The signal was averaged over 16 recordings, which corresponds to an improvement of signal-to-noise ratio by a factor of four. In our proof-of-principle experiment, the averaging is used to clean the acquired signal. The detected noise was observed to be predominantly of electrical origin and the averaged signal provides a hypothetical signal in presence of higher optical powers.
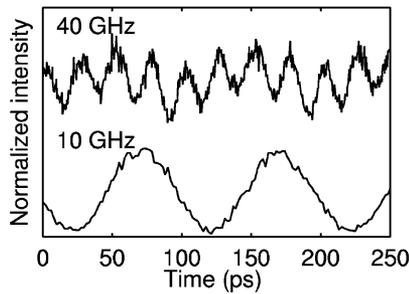
Fig. 4.   Recovered 10- and 40-GHz beat.

The quality of the 10-Gb/s signal varied channel-wise. Typically six, but a minimum of three consecutive zeros were always recovered, depending on how well the particular DFB was tuned to the resonance. The 40-GHz signal was measured with and without the other signals present. In both cases the beat was present, though noisier when other channels were also consuming the available amplification of the last-stage EDFA. The 40-GHz beat in absence of the other channels is presented in Fig. 4. For comparison, a short section of the 10-GHz beat from one of the 10-Gb/s channels is also shown. Both signals are averaged $(n = 16)$ and they were captured at arbitrary moments of time. The signal for 10-Gb/s channels was measured to have a timing jitter of 3 ps, which originated mainly from amplitude fluctuations. The noise and jitter characteristics of a resonator-based CR are discussed in more detail in [12].

IV. CONCLUSION

We proposed a new all-optical CR scheme that is based on a simple device consisting of a single birefringent resonator and a polarizer. The scheme enables parallel processing of multiple wavelength channels and data rates, where the data rate is matched with resonator birefringence, not to the resonator FSR. The principle was demonstrated for 21 simultaneous DWDM channels, 20 carrying data at 10 and one at 40 Gb/s. The scheme can be extended to even more simultaneous data rates (e.g., 160 Gb/s in addition to 10 and 40 Gb/s) and to other types of modulation formats, such as carrier suppressed RZ modulation or different forms of phase-shift keying.

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