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All-optical passive clock extraction of 40 Gbit/s NRZ data using narrow-band filtering

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Abstract: A passive all-optical scheme for clock extraction from non-return-to-zero (NRZ) data has been proposed based on narrow-band filtering. Two equally effective embodiments of the proposed scheme have been demonstrated experimentally. A carrier-to-noise ratio (CNR) of 30 dB has been achieved at 40 Gbit/s using fiber Bragg gratings (FBG).

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1. Introduction

Clock recovery (CR) is essential for data recovery and regeneration of digital signals. Compared to the return-to-zero (RZ) format, CR of NRZ data requires pre-processing to extract the clock signal for clock recovery since there is no clock component in its radio frequency (RF) spectrum. So far several all-optical methods for clock extraction of NRZ data have been proposed; most of them operate by converting the NRZ format to the pseudo return-to-zero (PRZ) format [1-5]. The NRZ-to-PRZ conversion (temporal-domain) schemes can be either active or passive. In [1-3], active NRZ-to-PRZ conversions were achieved using (transient) gain saturation and/or self-phase modulation (SPM) in semiconductor optical amplifier (SOA) followed by filtering. These methods typically have low sensitivity, i.e., high input power requirement. Furthermore, the speed of operation is limited by the carrier dynamics of SOAs. In [4-6], passive fiber-based interferometers were used to generate PRZ...
data from NRZ data. These methods require interferometric (phase or polarization) stability. The only scheme that did not use NRZ-to-PRZ conversion takes advantage of the fact that, even though there is no clock component in the NRZ RF spectrum, there are optical clock components (at integer multiples of the clock frequency from the optical carrier) in the NRZ optical spectrum due to the finite rise and fall time of the NRZ signals [7]. The spectral-domain scheme in [7] used a Gaussian band-pass filter centered at an optical clock component to perform clock extraction by equalizing the power in the optical carrier and that clock component. In this letter, we show that finite rise time is only a necessary but not sufficient condition for the existence (non-existence) of the optical (RF) clock component. By further elucidating the role of the rise time and the relationship between the optical clock components and the RF clock components, we show that narrow-band filtering offers the best possible clock extraction performance using filtering only and is only 3 dB away from the fundamental limit for passive clock extraction. From a practical point of view, clock extraction using narrow-band filtering can simultaneously retain the NRZ data thus facilitate subsequently data recovery in the electronic domain. It can also be made bit-rate insensitive. Clock extraction using narrow-band filtering reduces the complexity, cost and power consumption of system and avoids instabilities of interferometric configurations.

2. Origin of electrical and optical clock components

The existence of optical clock components in the optical spectrum has been attributed to the finite rise and fall time of the NRZ signal [7]. It is not straightforward to understand why there is no clock component in the NRZ RF spectrum since the electrical NRZ signal also has a finite rise time as well. In this section we elucidate the role of the rise and fall time in the origin of the electrical and optical clock components. Figure 1 shows a typical electrical NRZ pulse \( s(t) \) with finite rise and fall time, e.g., resulting from low-pass filtering of an ideal square wave NRZ pulse. It can be decomposed into an ideal NRZ pulse \( s(t) \) and two residual pulses \( r_1(t) \) and \( r_2(t) \). The spectrum of \( s(t) \) is \( \sin c(2\pi f) \), which vanished at integer multiples of the clock frequency \( f_c = 1/T \) (or the bit rate). This is well understood as the reason why ideal NRZ signals do not have electrical clock components in its RF spectrum. (NRZ data signal can be constructed from convolution of the NRZ pulse with a series of delta functions representing data in the time domain. The RF spectrum of the NRZ data is therefore

![Fig. 1. Temporal pulse shape, decompositions and spectra of electrical (upper) and optical (lower) NRZ signal with finite rise and fall time.](image_url)
proportional to the spectrum of a single NRZ pulse.) The nature of the residual pulses is responsible for the same lack of clock components in the RF spectrum for practical NRZ signals with finite rise and fall time. There exists a certain symmetry in the rising edge and falling edge of typical NRZ pulses, namely \( r_1(t-T/2) = -r_2(t+T/2) = r(t) \) or \( r_1(t) = r(t+T/2) \) and \( r_2(t) = -r(t-T/2) \). Using the translation property of Fourier transform, the spectrum of the residual pulses is given by

\[
\tilde{R}(f) = R(f) e^{i(2\pi f T/2)} - R(f) e^{-i(2\pi f T/2)}
\]

where \( R(f) \) is the Fourier transform of \( r(t) \). Due to the aforementioned symmetry, \( \tilde{R}(f) \) also vanishes at integer multiples of the bit rate. Therefore no clock component exists in the RF spectrum of electrical NRZ signals even with finite rise and fall time as shown in Fig. 1. However, when the electrical NRZ signal \( S_e(t) \) is applied onto an optical intensity modulator to modulate a continuous wave (CW) laser, the intensity of the modulated signal is proportional to \( S_e(t) \) while the amplitude of the modulated optical signal \( S_o(t) \) is proportional to \( S_e(t)^{1/2} \), which is shown at the bottom of Fig. 1. This effect results in the loss of symmetry in the rising and falling parts of each optical NRZ pulse so that \( r_1'(t-T/2) \neq -r_2'(t+T/2) \). The spectrum of the residual pulses no longer vanishes at integer multiples of the bit rate from the optical carrier. Therefore optical clock components do exist in the optical spectrum of NRZ signals with finite rise and fall time. This is verified by the spectral lines at integer multiples of clock frequency from the optical carrier in the optical modulation spectrum shown in Fig. 1.

3. Principle of clock extraction using narrow-band optical filtering

In this section we present the principle of clock extraction using narrow-band optical filtering for the case of a pseudorandom bit sequence (PRBS), \( d(t) \), of length \( N \) bits (or temporal duration \( NT \)). After modulation, the field of the NRZ modulated optical signal can be written as a Fourier series

\[
S_o(t) = A_0 \sqrt{d(t)} \cdot \exp(j\omega_0 t) = \left[ a_0 + \sum_{n \neq 0} a_n \exp(jn\omega_0 t) \right] \cdot \exp(j\omega_0 t)
\]

where, \( \omega_0 \) is the carrier frequency, \( a_0 = 2\pi/NT \). \( a_0 \) and \( a_n \) are the Fourier coefficients for the DC and \( n \)th harmonic component of \( \sqrt{d(t)} \), respectively. The Fourier coefficients, \( a_{N/2} \) and \( a_{-N/2} \), represent the clock frequency components in the optical spectrum. Based on the above analysis, \( a_{\pm N/2} \neq 0 \) when electrical NRZ pulses have finite rise time and fall time with symmetry defined above. The photodetected electrical signal is proportional to the optical intensity and can be expressed as

\[
S_e(t) = a_0' + \sum_{n \neq 0} a_n' \exp(jn\omega_0 t) \propto |S_o(t)|^2
\]

in which the electrical clock component in the RF spectrum can be represented as

\[
a_{N/2} = \sum_{n=0, N, 2N, \ldots} a_n a_{n-N} + \sum_{n=0, N, 2N, \ldots} a_n a_{n+N}
\]

The first term in Eq. (4) represents the contribution to the electric clock component from beating among the optical clock components and the optical carrier. The second term represents the contribution to the electrical clock component from beating among data components in the optical modulation spectrum. The first term is mainly determined by the beating between the optical carrier and the two adjacent optical clock components, which is at
least 40 dB larger than the strongest beating signal between the optical clock components. Similarly, the second term in Eq. (4) can be mainly attributed to the beatings of optical data components in the mainlobe of the optical spectrum. Thus the electrical clock component can be approximately expressed as

\[ a'n \approx a_0(a_{-N} + a_N) + \sum_{n=1}^{N-1} a_n a_{-n-N} \]  

(5)

The two terms in Eq. (5) cancel each other, which results in vanishing electrical clock components. If the optical carrier \( a_0 \) or the optical clock components \( a_{\pm N} \) are removed using narrow-band filtering, \( a_n' \) will only contain contributions from beating among data components thus the clock is extracted in the electrical domain. Removing the carrier or optical clock components will produce the same amount of the electrical clock. Even though the approach in [7] makes intuitive sense in that equalizing the optical clock component and the optical carrier would maximize the modulation index of an electrical clock (i.e. beat) signal to 100%, it is in fact a suboptimal clock extraction approach. The aforementioned electrical clock (beat) signal actually cancels the clock signal resulting from beating among data components, which is the real source of the extracted clock signal observed experimentally.

4. Experimental setup and results

The experimental setup for the proposed all-optical clock extraction is shown in Fig. 2(a). The 40G bit/s NRZ data is generated by externally modulating a CW tunable laser with a 2\(^{31}-1\) PRBS from a pulse pattern generator (PPG). The chirp parameter of the modulator is less than 0.4. FBGs operating in transmission mode are used to perform clock extraction through narrow-band optical filtering. The FBGs used in our experiment have a length of 12.9 cm and center wavelength around 1550 nm. The reflectivity of the FBGs is more than 99%. The insertion loss of each FBG is 0.2 dB. The 3-dB bandwidth of the FBGs is 0.032 nm (~4 GHz) with a rejection of more than 20 dB as shown in Fig. 2(b). In the optical carrier-removal approach, a single FBG was employed to remove the optical carrier from the optical spectrum of NRZ data while leaving other frequency components intact. In the optical clock-component-removal approach, two FBGs were used to remove the two optical clock components closest to the optical carrier. The optical signals in the experiment were analyzed by an optical spectrum analyzer and converted to the electrical signals using a 60 GHz photodetector. The electrical signals were amplified by a 50 GHz RF amplifier and characterized using a RF spectrum analyzer in the spectral domain and a wide-bandwidth sampling oscilloscope in the time domain.

The experimentally measured optical and electrical spectra of the input 40 Gbit/s NRZ data are shown in Fig. 3. The average optical power was 9.95 dBm before narrow-band
filtering. A carrier with peak power of 8.65 dBm and two optical clock components about 0.3 nm (~40 GHz) apart from the carrier were observed in the optical modulation spectrum in Fig. 3(a). The optical clock components would be more significant if an optical spectrum analyzer with higher resolution was used. Figure 3(b) shows the corresponding electrical spectrum. A weak electrical clock component at 40 GHz was present due to imperfect multiplexing in the generation of the electrical NRZ data. The clock power and carrier-to-noise ratio (CNR) were -31.83 dBm (-52.83 dBm without electrical amplification) and 14.5 dB, respectively. The relatively high optical power was used in the experiments for ease of characterization. The performance of the current passive clock extraction scheme including clock power enhancement and CNR enhancement is independent of the input optical power.

4.1 Optical carrier removal

In the optical carrier-removal approach, a single FBG was employed to remove the carrier from the modulation spectrum of NRZ data. Figure 4(a) shows the optical spectrum of the optical carrier-removed signal. The average power is about 0 dBm. The optical power is much lower compared to the input power since nearby data components were removed with the optical carrier due to the finite bandwidth of FBG. The RF spectrum of the carrier-removed signal is shown in Fig. 4(b). A clock power of -20.33 dBm and CNR of 31.33 dB were obtained after the carrier was removed. Figure 4(c) and (d) represent the simulated optical spectrum and RF spectrum using the carrier-removal approach. The simulation agrees very well with the experimental results. Compared to the RF spectrum of the input NRZ signal, the clock and CNR were enhanced by 11.5 dB and 16.83 dB, respectively, even though the average optical power was reduced by about 10 dB.

An important advantage of the optical carrier-removal approach is that it is bit-rate independent. We also investigated the robustness of the carrier-removal clock extraction approach to the detuning between the optical carrier frequency and the center frequency of the FBG. Experimental measurement showed that the optimal range is ±1.5 GHz from the center frequency of FBG well within the frequency stability of telecom lasers. Within this range, the clock power remains almost constant. The measured 3-dB tolerance to the carrier frequency detuning is about 3.8 GHz, which is very close to the simulation result of 3.65 GHz.
4.2 Optical clock-component removal

In the optical clock-component-removal approach, two FBGs were used to remove the two optical clock components closest to the optical carrier. Figure 5 shows the simulated and experimentally measured optical and electrical spectra of the clock-component-removed signal. The average optical power was 9.37 dBm. The power loss (0.58 dB) is very small compared to that in the carrier-removed case (9.95 dB) because the optical clock components contain much less power than the optical carrier. The optical carrier and the data components remain unchanged as shown in Fig. 5(a). Compared to the RF spectrum of input NRZ signal in Fig. 3(b), the clock and CNR were enhanced by 12.67 dB and 16.5 dB respectively while data components remain almost unchanged. Again, the experimental results agree well with the simulated optical and RF spectra of the optical clock-component-removed signal in Fig. 5(c) and (d). Similar to the optical carrier-removal approach, the 3-dB tolerance of the optical clock-component-removal approach to the carrier frequency detuning was about 3.6 GHz, which is also consistent with the simulation result of 3.65 GHz. Comparing the clock components in the simulated RF spectra of Fig. 4(d) and Fig. 5(d), it is seen that the optical carrier-removal approach and the optical clock-component-removal approach are equivalent for clock extraction, which is consistent with our analysis.
Fig. 5. (a) Measured optical spectrum, (b) Measured RF spectrum, (c) Simulated optical spectrum with resolution of 10 MHz (black) and 7.5 GHz (or 0.06 nm) (blue) and (d) Simulated RF spectrum of the optical clock-component-removed signal.

Fig. 6. (a) Eye diagram of the input 40 Gbit/s NRZ data (20 ps/div) (b) Eye diagram of the optical clock-component-removed signal (20 ps/div).

An important advantage of the optical clock-component-removal approach is that the NRZ data are retained in the clock extraction process. Figure 6 shows the experimentally measured 8 consecutive eye diagrams of the 40 Gbit/s NRZ signal before and after clock.
extraction. Compared to the input eye diagram, the clock-component-removed eye diagram exhibits nearly identical extinction ratio. 40 GHz oscillations on consecutive bit 1’s can be clearly observed, which is precisely the source of 40 GHz extracted clock in the RF spectrum.

5. Discussion and conclusion

In conclusion, a scheme for passive all-optical clock extraction of NRZ data using narrow band optical filtering has been proposed and two equally effective methods have been demonstrated in experiment and simulation. The results show carrier-to-noise ratio $>30$ dB can be achieved at 40 Gbit/s using both methods. The proposed scheme relaxes the complexity in processing and avoids the instability of interferometric structure. The carrier-removal method is insensitive to the bit rate, which is limited by the dynamics of SOA used in the nonlinear processing methods [8, 9]. The optical clock-component-removal method demonstrated for the first time clock extraction while retaining the original NRZ data.

The narrow-band optical filtering approach demonstrated in this paper works well for NRZ signal with chirp. In fact, chirp in the data will broaden its optical spectrum, therefore the optical clock components ($a_n, a_{-N}$ in Eq. (5)) and data components in the mainlobe ($a_n, n \neq 0, from -(N-1) to (N-1)$ in Eq. (5)) increase with increased chirp. As a result, more clock power can be extracted after filtering for NRZ signals with chirp. Compared to the chirp-free case [Fig. 4(d) and Fig. 5(d)] the clock power after filtering for an NRZ signal with a chirp factor of 2 increased to -10.91 dBm, an improvement of about 9.5 dB.

The clock extraction methods demonstrated experimentally in this paper removed the first term in Eq. (5). It is possible to extract a clock signal by alternatively removing the second term in Eq. (5). In this alternative approach, high Finesse Fabry-Perot filters with a free-spectral range equal to the bit rate can be used to filter out the data components in the optical spectrum while retaining the optical clock component. This approach will suffer from high insertion loss compared to using FBGs.

The narrow-band optical filtering approach demonstrated in this paper is 3 dB away from the fundamental limit for passive clock extraction of NRZ signals with finite rise time. Theoretically, it is possible to invert the phase of the optical carrier thus making the two terms in Eq. (5) add to each other. However, practically it might be difficult to invert only the phase of the optical carrier (or the optical clock components) without affecting the phase of the data components.

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