

# Optimizing Clock Enhancement to Achieve Modulation-Format-Independent All-Optical Clock Recovery

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**Abstract**—We investigate a clock enhancement technique with signal pre-distortion using a semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI). Working together with a Fabry-Perot filter (FPF) based all-optical clock recovery module, this technique achieved modulation-format-independent all-optical clock recovery with a simple and straight-forward configuration. We then analyze the clock enhancement technique with numerical simulations. The simulations determine the optimal operation points of the SOA-MZI for RZ and NRZ inputs and demonstrate effective clock amplitude improvement and clock amplitude fluctuation reduction.

## I. INTRODUCTION

OPTICAL reamplification, reshaping and retiming (3R) regeneration is an important enabling technology that ensures scalability and robustness in future all-optical networks. To achieve full 3R optical regeneration, we need to realize all-optical clock recovery without requiring high-speed electronics. Previous research has demonstrated a number of all-optical clock recovery techniques [1,2,3,4]. However, most of these techniques can only work with either return-to-zero (RZ) or non-return-to-zero (NRZ) format. Hence, modulation-format-dependence becomes a drawback for implementation. Recently, we have proposed a clock enhancement technique that uses signal pre-distortion in a semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI) [5,6]. In this paper, we investigate this technique with a simulation model using realistic SOA-MZI parameters and demonstrate that modulation-format-independent all-optical clock recovery can be achieved with a simple configuration. The numerical simulations also locate the optimal operation points of the SOA-MZI for various input encodings (e.g. RZ and NRZ). Effective clock amplitude improvement and clock amplitude fluctuation reduction can be achieved for all-optical clock recovery with the optimization.

## II. ALL-OPTICAL CLOCK RECOVERY WITH FPF

All-optical clock recovery can be achieved through extracting the clock spectral components from optical

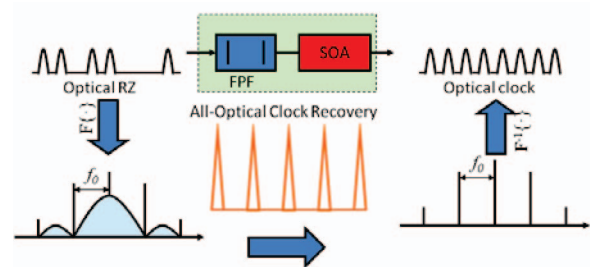


Fig. 1 Operation principle of all-optical clock recovery with a FPF and a SOA

signals with narrowband optical filtering. A Fabry-Perot filter (FPF) with a free spectral range (FSR) matched to the signal bit-rate, and a relatively large finesse (typically  $> 50$ ) works effectively in this situation [4,7]. Fig. 1 explains the operation principle of the all-optical clock recovery module that is built with a FPF and a semiconductor optical amplifier (SOA). The optical spectrum of the return-to-zero (RZ) signal consists of continuous spectral components from data modulation and line spectral components from the clock and its harmonics. When passing through the all-optical clock recovery module, the clock spectral components get transmitted, while the data modulation components get suppressed. The FPF removes most of the data modulation and provides optical clock pulses

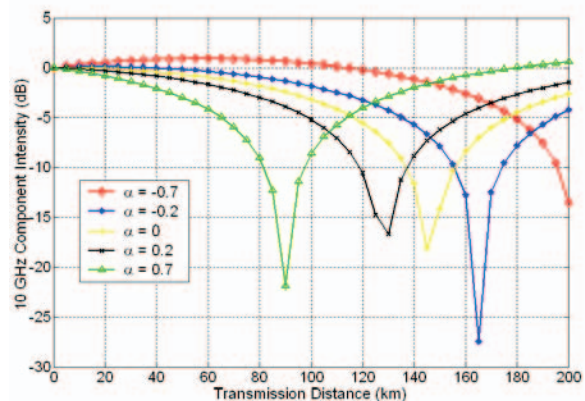


Fig. 2 Intensity of recovered 10 GHz clock component vs. LEAF fiber transmission distance

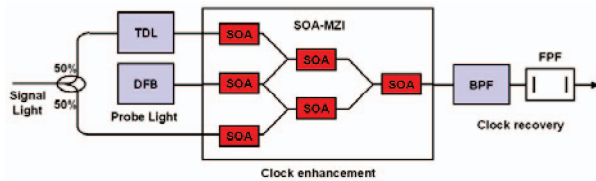


Fig. 3 Setup of the all-optical clock enhancement and recovery module

matching to its FSR (i.e. signal bit-rate) frequency. However, when the data modulation contents long sequences of repeated zeros, the recovered clock amplitude can decay due to pattern-dependence [7]. This is the reason why the module has to include a gain-saturated SOA to reduce the pattern-dependent amplitude variations [4]. The limiting amplification in the saturated SOA helps suppress the residual data modulation and enhances the recovered clock's side-lobe suppression ratio.

### III. SIGNAL PRE-DISTORTION FOR CLOCK ENHANCEMENT

We have discussed FPF-based all-optical clock recovery for undistorted RZ signals in Section II. However, during fiber transmission, physical layer impairments, such as amplifier noise, chromatic dispersion (CD), polarization-mode dispersion (PMD), and fiber nonlinearities can degrade signal quality and input a distorted signal to the all-optical clock recovery module. Fiber dispersions such as CD and PMD add complexity to clock recovery due to the clock RF fading effect [8]. Due to the fact that RF fading can attenuate the magnitude of the clock frequency components in signal spectrum, the performance of the all-optical clock recovery will be strongly affected. Fig. 2 plots the intensity of the 10 GHz frequency component vs. the large-effective-area fiber (LEAF) ( $D = 4.25$  ps/nm/km) transmission distance at  $\lambda = 1552.5$  nm. The parameter  $\alpha$  is the frequency chirp of the initial modulation. The RF fading induced by CD causes large-swing ( $> 20$  dB) intensity fluctuation of the clock component. Without pre-knowledge of the transmitter chirp  $\alpha$  and the total dispersion, it is difficult to predict the intensity fluctuation. Moreover, when the signal is encoded in the non-return-to-zero (NRZ) format, the clock spectral components can be even weaker [6]. To overcome this drawback, we have proposed an all-optical clock enhancement technique that uses signal pre-distortion in a semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI) [5,6].

Fig. 3 shows the setup of the all-optical clock enhancement and recovery module. The SOA-MZI is in a push-pull operation, which injects the same optical signal into both interferometric arms of the SOA with a relative time delay. The SOA-MZI works in an over-driven mode in which the device is driven across the minimum point on its power transfer function [5]. Fig. 4 shows the simulated eye-diagrams for clock recovery from dispersed RZ signal. The 10 Gb/s input signal is encoded with pseudorandom bit

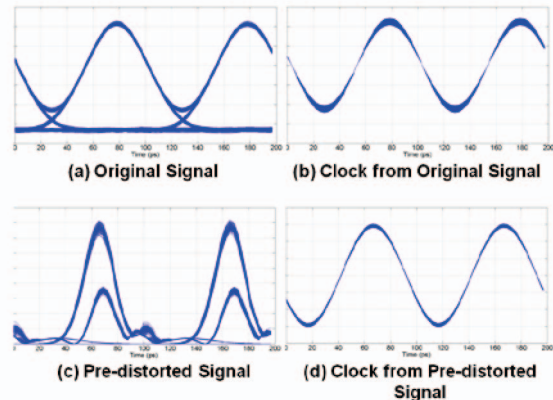


Fig. 4 Simulated eye-diagrams for clock recovery from dispersed RZ signal

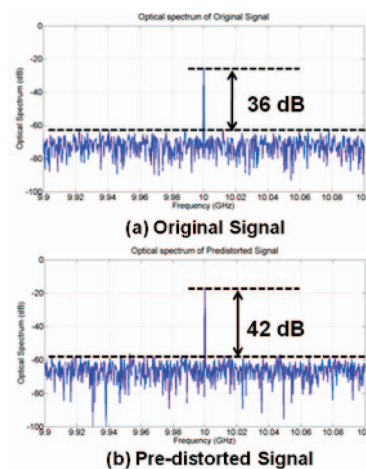


Fig. 5 10 GHz clock spectra for (a) without and (b) with clock enhancement for dispersed RZ input

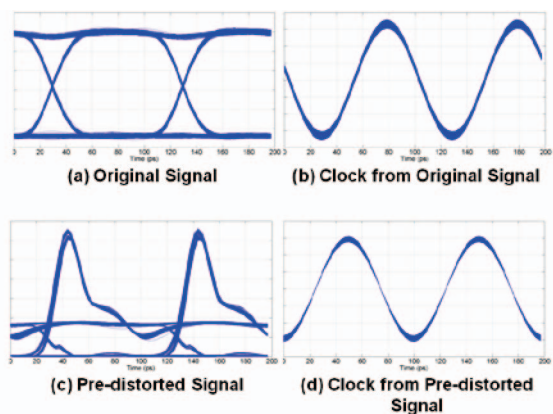


Fig. 6 Simulated eye-diagrams for clock recovery from NRZ signal

sequence (PRBS)  $2^{31}-1$ . As shown in Fig. 4(c), a portion of the leading and falling edges of the bit "1" pulses can be flipped up and be extended into the adjacent bit "0" slots. This enhances the clock component by inserting pulses in the bit "0" slots. Also, the pulse-width of the pre-distorted signal is narrower than the original signal, and this enhances the clock component by sharpening the signal. By comparing the recovered clocks in Fig. 4(b) and (d), we can

see that the pre-distortion reduces both the timing jitter and the amplitude fluctuation on the recovered clocks. Fig. 5 compares the 10 GHz clock spectra for cases with and without clock enhancement. With the same average input

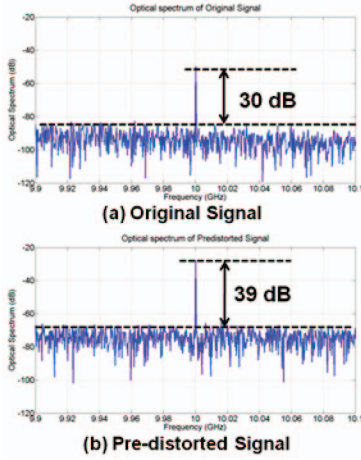


Fig. 7 10 GHz clock spectra for (a) without and (b) with clock enhancement for NRZ input

power, the clock enhancement improves the carrier-to-noise-ratio (CNR) by 6 dB, and increases the power of the 10 GHz clock component by ~10 dB.

Fig. 6 shows the simulated eye-diagrams for clock recovery from NRZ signal. The pre-distortion creates RZ-like pulses and overcomes the spectral notch at clock frequency of the NRZ signal. Fig. 7 shows the comparison of the 10 GHz clock spectra with and without clock enhancement. With the same average input power, the clock enhancement improves the CNR by 9 dB, and increases the power of the 10 GHz clock component by ~20 dB.

IV. SIMULATION AND RESULTS ANALYSIS

To determine the optimal operation points of the SOA-MZI for the clock enhancement, we build a simulation model with realistic SOA-MZI parameters and investigate the clock enhancement technique with numerical simulations. The output of the SOA-MZI can be modeled as [9]:

$$I_{out}(t) = I_0[G_1(t) + G_2(t) + 2\sqrt{G_1(t) \cdot G_2(t)} \cdot \cos(\phi_1(t) - \phi_2(t))] \quad (1)$$

where  $I_0$  is the intensity of the probe light,  $G_1(t)$  and  $G_2(t)$  are the gains probe light get from the two arms, and  $\phi_1(t)$  and  $\phi_2(t)$  are the phases of the probe lights before interference. We assign the initial gain of the SOA as 10 dB, and the gain recovery time as 25 ps. The 10 Gb/s input signal is encoded with PRBS  $2^{31}-1$ . The FPF has a FSR of 10 GHz and a finesse of 100. The simulations investigate both the RZ and NRZ format, and the full-width at half-maximum (FWHM) is 20, 50, or 90 ps for the RZ pulses. In the simulations, we scan the signal input power and relative delay between the two SOA-MZI arms in the

simulations. The amplitude of the input signal is normalized with the  $\pi$ -switching power (optical power to achieve  $\pi$  phase difference between the two arms) of the SOA-MZI, and the relative delay is changed from 10 to 90 ps. As shown in the contours in Fig. 8-11, the clock enhancement with signal pre-distortion not only improves the amplitude of the recover clocks, but also reduces the amplitude fluctuation.

The simulations also successfully locate the optimal operation points of the SOA-MZI for clock enhancement, in the cases. For example, when the FWHM of the input RZ pulse is 50 ps, if we make sure the signal input power is within  $[0.15, 0.2]$   $\pi$ -switching power and the relative delay is within  $[20, 30]$  ps, the amplitude of the recovered clock can be increased by 4.5 dB and the amplitude fluctuation can be reduced by 1 dB. For the NRZ inputs, when the input power is within  $[0.25, 0.3]$   $\pi$ -switching power and the relative delay is within  $[30, 40]$  ps, the clock amplitude can be increase by around 12 dB and the amplitude fluctuation can be reduced by 2 dB.

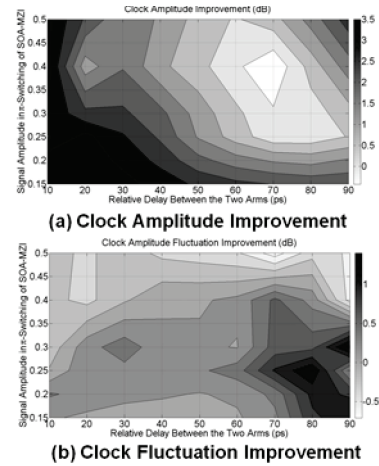


Fig. 8 Contours of (a) clock amplitude improvement and (b) clock fluctuation improvement for RZ signal with pulse FWHM = 20 ps.

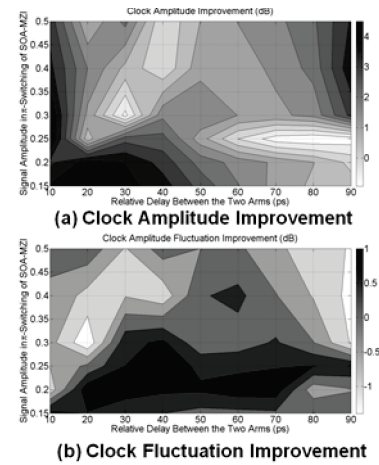


Fig. 9 Contours of (a) clock amplitude improvement and (b) clock fluctuation improvement for RZ signal with pulse FWHM = 50 ps.



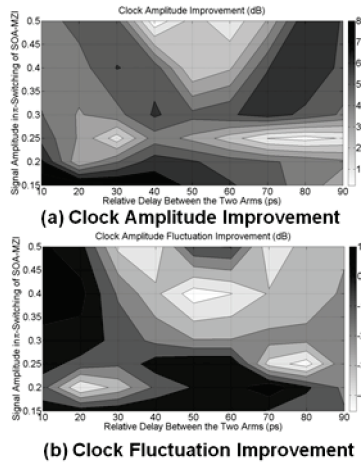


Fig. 10 Contours of (a) clock amplitude improvement and (b) clock fluctuation improvement for RZ signal with pulse FWHM = 90 ps.

## V. CONCLUSION

We investigated a clock enhancement technique with signal pre-distortion using a SOA-MZI. Working together with a FPF-based all-optical clock recovery module, this technique achieved modulation-format-independent all-optical clock recovery with a simple and straight-forward configuration. To determine the optimal operation points of the SOA-MZI for clock enhancement, we built a simulation model with realistic SOA-MZI parameters. The simulation results showed that the pre-distortion by SOA-MZI could sharpen the clock components in the input signal and reduce both the timing jitter and amplitude fluctuations on the recovered clocks. By scanning the input signal power and relative delay between the two SOA-MZI arms, we determined the optimal operation points of the SOA-MZI for RZ and NRZ inputs and achieved effective clock amplitude improvement and clock amplitude fluctuation reduction.

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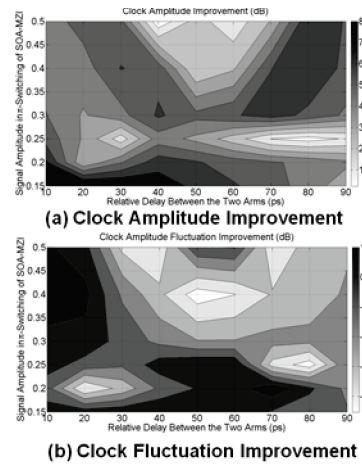


Fig. 11 Contours of (a) clock amplitude improvement and (b) clock fluctuation improvement for NRZ signal.

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