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All-Optical NRZ-to-PRZ Format Conversion Limitations Using Notch Filters

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***Abstract*—In this paper all-optical non-return to zero to pseudo-return to zero format conversion limitations, using optical notch filters, are evaluated numerically. Open source simulation toolbox Optilux was used for simulations. Gauss and short term integrator notch filter performance and full width half maximum bandwidth impact on format conversion at transmission speed up to 40 Gbit/s was compared. Then format conversion performance was evaluated in a cascade of single ring microring resonators. Results show that large depth of an optical notch filter can cause two pulses generation at the edges of input pulses and lead to clock signal degradation.**

***Index Terms*—All-optical clock recovery, optical signal processing, optical resonators, notch filters.**

I. INTRODUCTION

Photonic technologies for optical communications have gained great breakthrough in last years, because of high demand for bandwidth from consumers and need to reduce costs per every transmitted bit from service provider side [1]. To overcome these obstacles various optical modulation formats have been created for optical transmission [2]. These achievements lead to need to perform signal processing in optical domain to increase the performance of transmission in terms of lower latency [3].

All-optical signal processing field is growing fast and multiple capabilities been shown recently [4-7]. One of the key features for digital signal is clock recovery (CR) to perform transmitted data recovery and/or regeneration. There are several demonstrations for non-return to zero on-off keying (NRZ-OOK) modulation format CR. Large part of demonstrations focus on well-known NRZ-OOK to pseudo-return to zero (PRZ) format conversion, which could be performed with i) linear methods: fibre Bragg grating (FBG)-based notch filters [8], Fabry–Perot optical band-pass or comb filters [9] or ii) nonlinear methods: using self-phase modulation in a semiconductor optical amplifier [10].

Nonlinear methods are related to high input power, which results in additional nonlinear crosstalk and reduced energy efficiency of overall transmission system [11]. Most conventional are linear methods, but due to large size are impractical for small scale on-chip optical signal processing. However recent demonstrations have shown NRZ-to-PRZ format conversion with single ring and double ring microring resonators (MRR) at gigabit speeds [5]. This approach seems to be more advanced in terms of on-chip devices. However there are limitations of this technique to increase the transmission speed: the converted pulse amplitude is highly reduced and the width is increased [5].

In this paper we detail our systematic simulation study to point out other limitations of NRZ-to-PRZ format conversion using notch filters. At first we compare Gauss and short term integrator notch filters performance and full width half maximum (FWHM) bandwidth influence at transmission speed up to 40 Gbit/s. Then conversion performance is evaluated in cascade of single ring microring resonator (MRR). Results show that increase of notch filter depth can cause two pulses generation at the edges of input NRZ pulses and lead to recovered clock signal degradations.

II. SIMULATION METHOD AND SETUP

In this paper Optilux simulation tool was used to evaluate the performance of NRZ-to-PRZ conversion. It is an open source collection of tools that provide advanced techniques to design, simulate, and analyse optical communication systems and is implemented as a Matlab toolbox. The principle of format conversion is shown in Fig. 1.

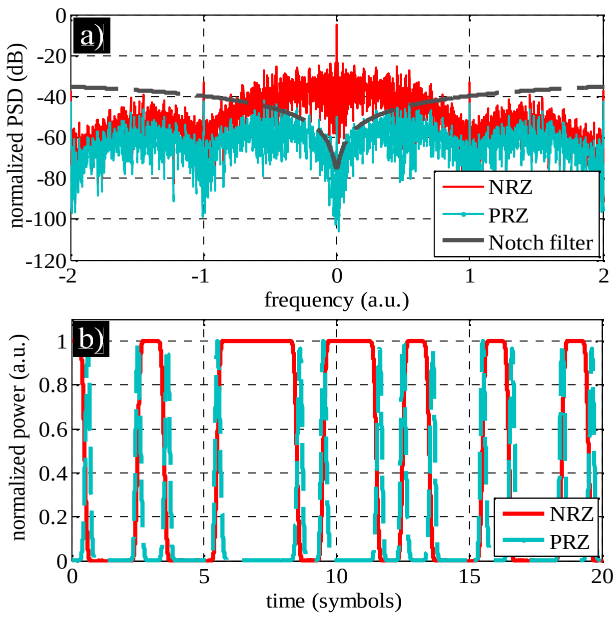

Fig. 1. Principle of NRZ-to-PRZ format conversion with notch filter, (a) NRZ and PRZ spectrum, (b) NRZ and PRZ pulses.

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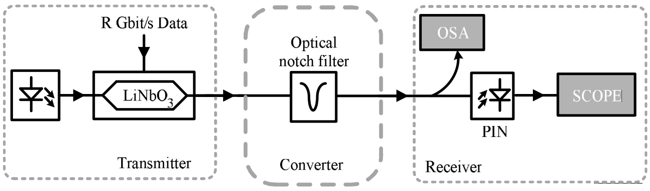

Fig. 2. Setup of NRZ-to-PRZ format conversion with optical notch filter.

The setup for NRZ-to-PRZ conversion (see Fig. 2) consists of three parts: optical transmitter, format converter and optical receiver. The optical transmitter for NRZ-OOK optical signal generation consists of $LiNbO_3$ Mach Zehnder modulator (MZM) and continuous wave (CW) light laser. MZM was driven by pseudo random binary sequence (PRBS) with an additional zero added to the longest sequence of zero. Pulses with raised cosine behaviour were used in simulations. The frequency in simulations is dimensionless and filter bandwidths are normalized as well. After converter the PRZ optical signal was detected in optical receiver, which consists of photodiode (PIN), optical spectrum analyser (OSA) and electrical scope. Three optical notch filter transfer functions were implemented in simulator. First two of them were adapted from the existent Optilux library to ensure the Gauss (1) and short term integrator (2) notch filters:

$$H(f)=1-\left|\exp(-0.5\cdot\log(2)\cdot f^2)\right|^2, \quad (1)$$

$$H(f)=1-\left|\frac{\sin(f)}{f}\right|^2. \quad (2)$$

The amplitude square transfer functions of these filters are shown in Fig. 3. Both filters are chosen with equal full width half maximum (FWHM) bandwidths.

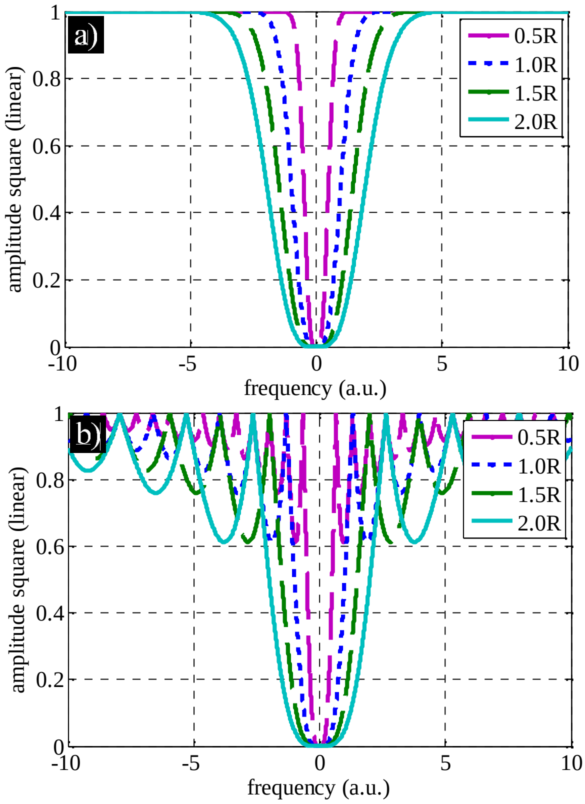

Fig. 3. Amplitude square transfer functions of (a) Gauss and (b) short term integrator notch filters with half FWHM bandwidths shown in inset.

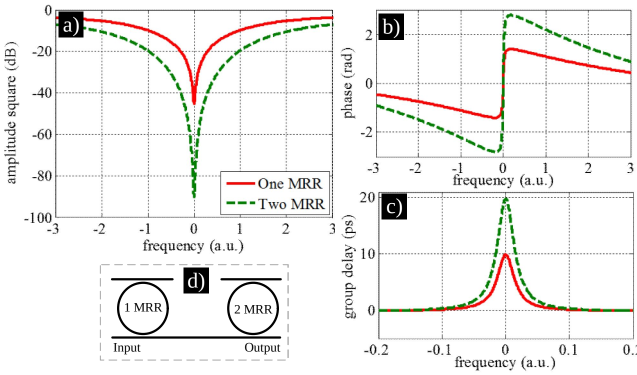

Fig. 4. Amplitude square transfer (a), phase (b) and group delay (c) functions of single ring MRR notch filter with $k_{1,2}$ = 0.8, α_r = 0.99 and FSR = 10R, where R is transmission speed. The inset (d) is showing setup of MRR cascade. Amplitude square transfer function is shown after one MRR (red line) and after two MRR (green dotted line).

Notch filter bandwidths are normalized to transmission speed and in current work the value of half FWHM bandwidths was chosen to be 0.5R, 1.0R, 1.5R and 2.0R, where R is transmission speed of optical signal. As one can see from the transfer functions of optical notch filters no loss was assumed to be present at transfer functions. This was done to evaluate only the influence of amplitude square transfer function form on format conversion.

For further simulations single ring MRR optical notch filter was implemented in simulation program library. The model for optical signal processing with MRR is defined as follows [4], [6]

$$H(f)=\frac{\sqrt{1-k_2}-\sqrt{1-k_1}\cdot\sim_r^{2}\cdot\exp\left\{-j\cdot 2\cdot\text{®}\cdot\left(\frac{f-f_0}{FSR}\right)\right\}}{1-\sqrt{1-k_1}\cdot\sqrt{1-k_2}\cdot\sim_r^{2}\cdot\exp\left\{-j\cdot 2\cdot\text{®}\cdot\left(\frac{f-f_0}{FSR}\right)\right\}}, \quad (3)$$

where $k_{1,2}$ is the waveguide power coupling coefficient, α_r is the round-trip cavity loss factor (α_r = 1 for an ideal lossless transmission), *FSR* is free spectral range or distance between two spectral minimums. In Fig. 4 the complex transfer functions of cascaded single ring MRR optical notch filters are shown. As one could see from graphs there is a small change in phase and group delay for cascaded single ring MRRs optical notch filters [12], [13].

III. RESULTS AND DISCUSSION

To evaluate NRZ-to-PRZ format conversion optical 1.25 Gbit/s, 2.5 Gbit/s, 10 Gbit/s and 40 Gbit/s NRZ-OOK optical signal was generated using setup shown in Fig. 2.

Then generated optical signals were filtered with Gauss or short term integrator notch filter with different FWHM bandwidth. As one can see from Fig. 5 converted PRZ signal pulses are formed at the edges of NRZ-OOK signal pulses (as shown in Fig. 1) when the bandwidth of notch filter is increased. All spectrums and pulses are normalized to input signal therefore input signal (Fig. 6) power spectrum density (PSD) maximum is at 0 and pulse amplitude is 1. From results the amplitude square transfer functions influence is negligible at larger FWHM bandwidth values.

To ensure that conversion is resistant to channel central's frequency fluctuations additional simulations were carried out. The fluctuations diapason was chosen to be ±0.3R. Figure 7 and Fig. 8 shows 1.25 Gbit/s NRZ-OOK optical signals after Gauss and short term integrator notch filter with 4R FWHM bandwidth.

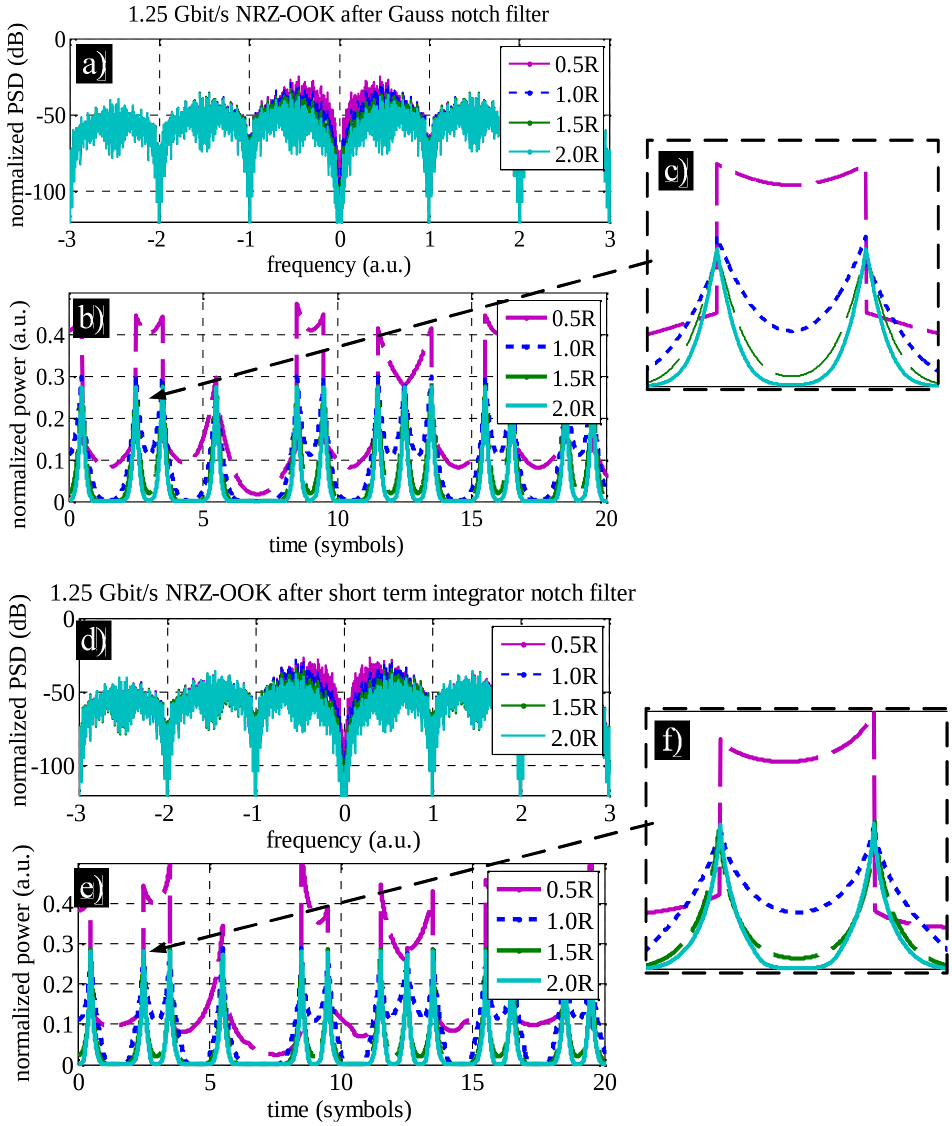

Fig. 5. 1.25 Gbit/s NRZ-OOK optical signals (a, d) spectrum, (b, e) pulses, (c, f) 3rd pulse magnification after Gauss (a, b, c) and short term integrator (d, e, f) notch filters with half FWHM bandwidths shown in inset.

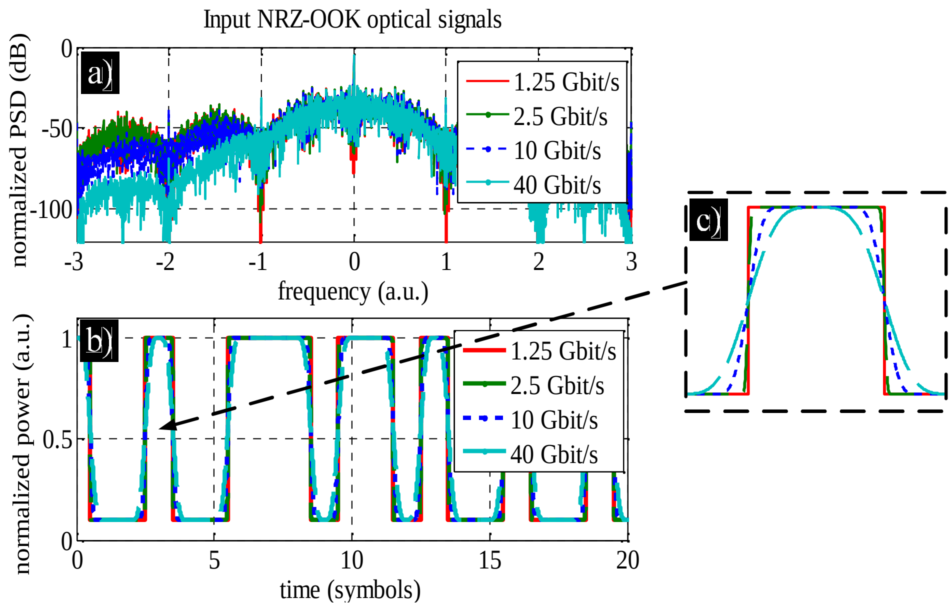

Fig. 6. Input 1.25 Gbit/s, 2.5, 10 and 40 Gbit/s NRZ-OOK optical signals (a) spectrum, (b) pulses, (c) 3rd pulse in magnification.

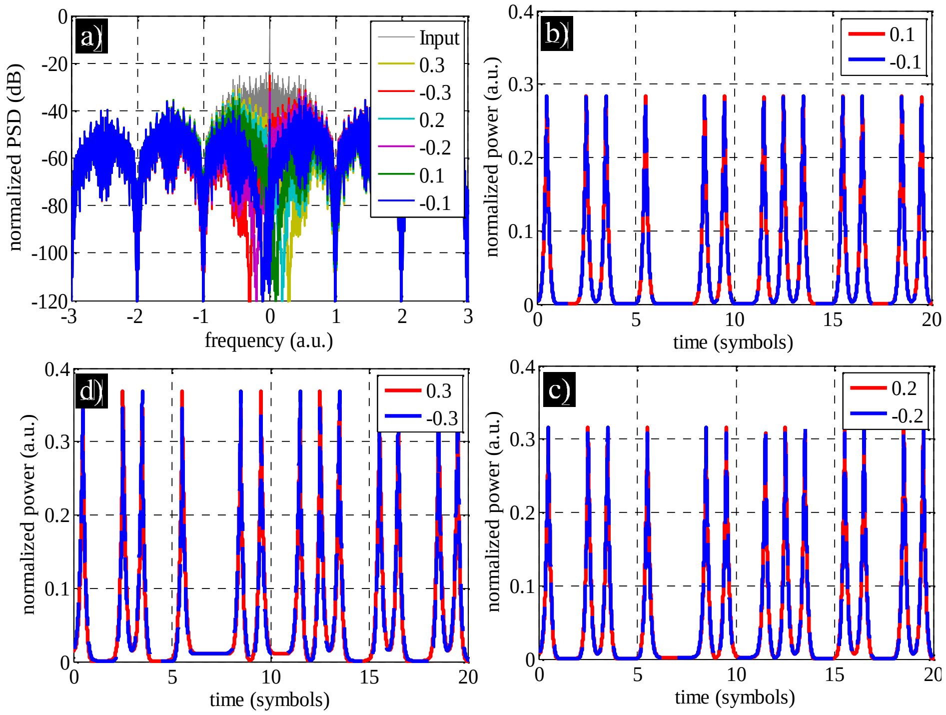

Fig. 7. 1.25 Gbit/s NRZ-OOK optical signals (a) spectrum, (b) pulses at ±0.1R, (c) pulses at ±0.2R and (d) pulses at ±0.3 after Gauss notch filter with 4R FWHM bandwidth.

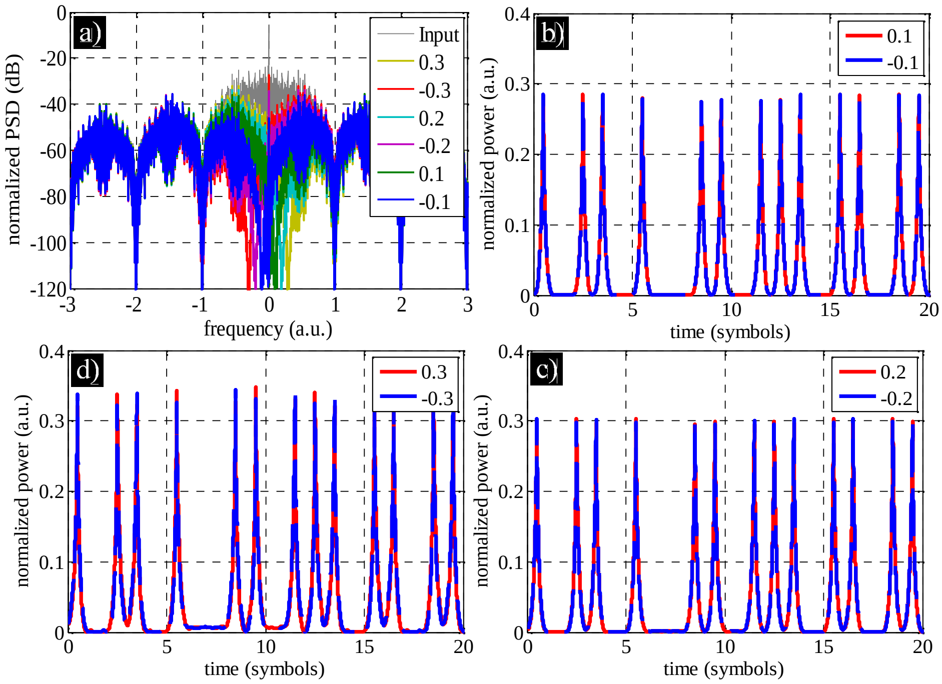

Fig. 8. 1.25 Gbit/s NRZ-OOK optical signals (a) spectrum, (b) pulses at ±0.1R, (c) pulses at ±0.2R and (d) pulses at ±0.3 after short term integrator notch filter with 4R FWHM bandwidth.

As one can see from the results slight notch filter offset from channels central frequency gives higher amplitude values of generated PRZ pulses. In the case of both optical notch filters the tendency is the same, but in the case of Gauss notch filter pulses amplitude is slightly higher. This could be used as a benefit from channel central's frequency changes, which are caused from temperature fluctuations.

In Fig. 9 at the edges of 2.5 Gbit/s NRZ-OOK pulses after Gauss and short term integrator notch filters with 0.5R, 1.0R, 1.5R and 2.0R half FWHM bandwidths are shown. As one can see from the results two PRZ pulses were generated. This effect was not observed with steeper pulses. The problem appears when the pulses have higher rise and fall times. This was concluded from additional simulations carried out at higher speed (2.5 Gbit/s and higher). The converted PRZ pulse amplitude was reduced and two pulses generation were obtained, which leads to optical clock signal degradation.

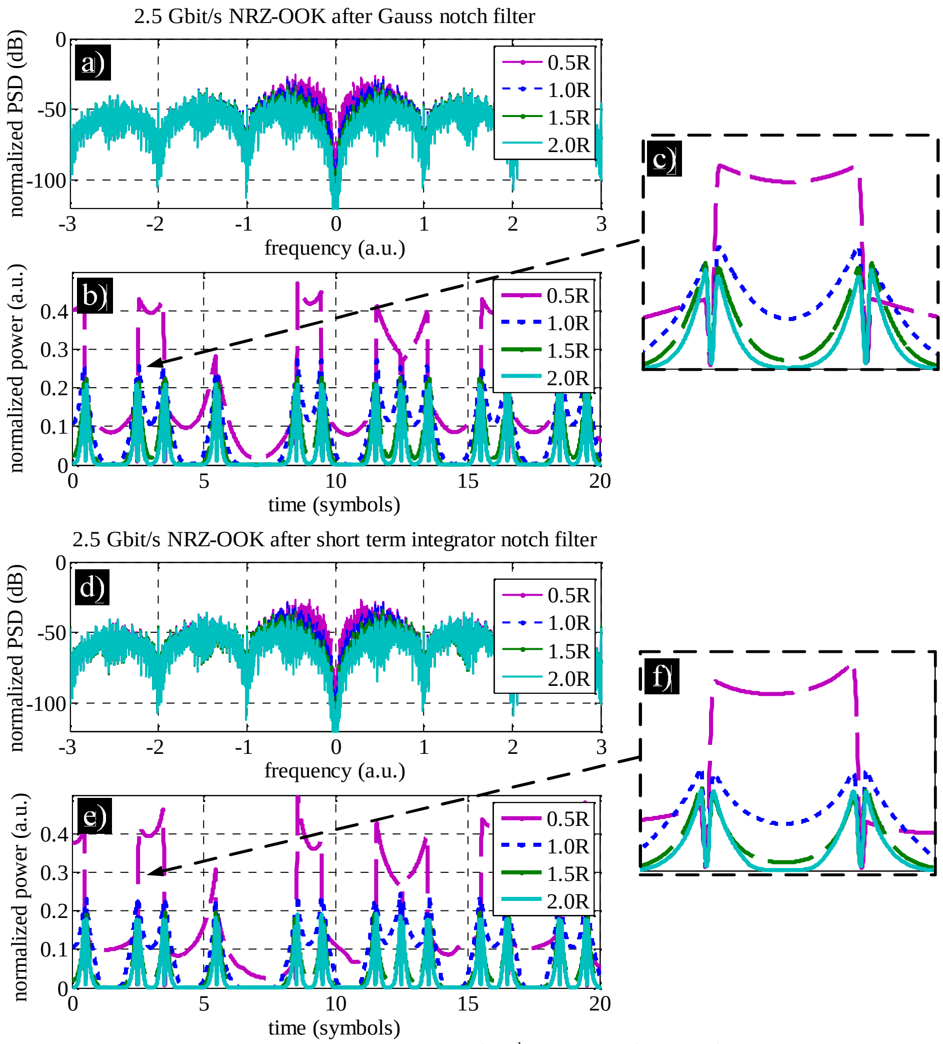

Fig. 9. 2.5 Gbit/s NRZ-OOK optical signals (a, d) spectrum, (b, e) pulses, (c, f) 3rd pulse magnification after Gauss (a, b, c) and short term integrator (d, e, f) notch filters with half FWHM bandwidths shown in inset.

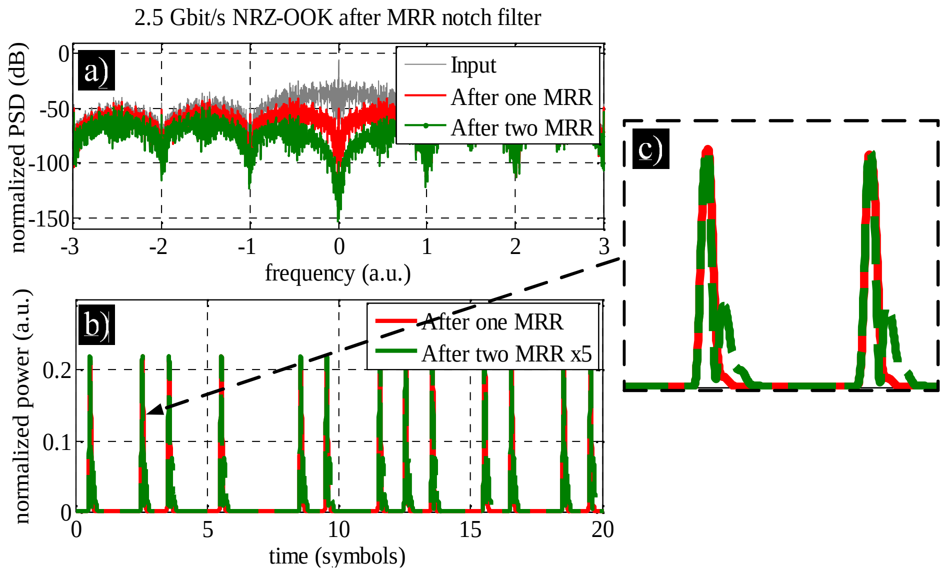

Fig. 10. 2.5 Gbit/s NRZ-OOK optical signals (a) spectrum, (b) pulses, (c) 3rd pulse magnification after single ring MRR notch filters with 4.0R FWHM bandwidth.

There are demonstrations of NRZ-to-PRZ conversion at 3.6 Gbit/s with single ring and double ring MRR [5]. To point out the limitations of this method at higher transmission speed (>3.6 Gbit/s) additional simulations were carried out. The cascade configuration (see inset on Fig. 4) for format converter based on single ring MRR was used. In Fig. 10 2.5 Gbit/s NRZ-OOK optical signals after single ring MRR notch filters with 4.0R FWHM bandwidth are shown. Converted PRZ pulses amplitude after one a single ring MRR is lower comparing to Gauss or short term integrator notch filter with same FWHM bandwidth. The pulse amplitude is even more reduced after two single ring MRR's and small second pulse is generated right after the primary pulse, which shows the presence of two pulse generation at the edges of NRZ-OOK pulse.

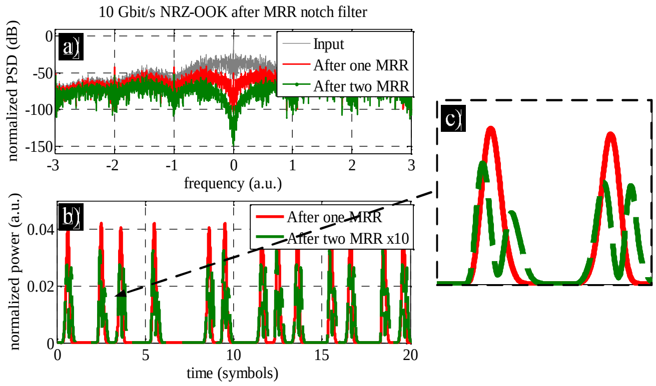

Fig. 11. 10 Gbit/s NRZ-OOK optical signals (a) spectrum, (b) pulses, (c) 3rd pulse magnification after single ring MRR notch filters with 4.0R FWHM bandwidth.

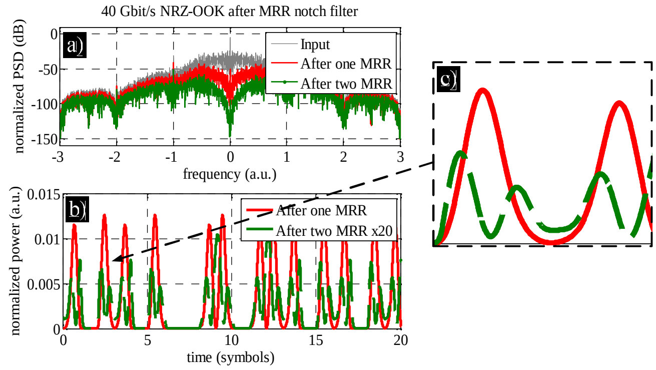

Fig. 12. 40 Gbit/s NRZ-OOK optical signals (a) spectrum, (b) pulses, (c) 3rd pulse magnification after single ring MRR notch filters with 4.0R FWHM bandwidth.

10 Gbit/s and 40 Gbit/s NRZ-OOK signals after single MRR notch filters with 4.0R FWHM bandwidth is shown in Fig. 11 and Fig. 12, accordingly. The converted PRZ pulses after one single MRR has greatly reduced amplitude, which becomes even worse with increased pulse rise and fall times. In the case of 10 Gbit/s after two single ring MRR's two PRZ pulses generated at the edge of NRZ-OOK pulse have almost the same amplitude, which comparing to 2.5 Gbit/s transmission speed can cause even greater optical clock signal degradation. The 3rd pulse magnifications on Fig.10–12 are shown with same start and end times. This shows another limitation of this method, which leads to degradation of optical clock signal. PRZ pulses have ~4 times width difference in width comparing 2.5 Gbit/s and 40 Gbit/s transmission speed.

IV. CONCLUSIONS

In this paper NRZ-to-PRZ conversion limitations with optical notch filters were observed at transmission speed up to 40 Gbit/s. Results shows that optical notch filter FWHM bandwidth and depth affect the converted PRZ pulses. At higher optical notch filter depths for NRZ-OOK pulses with larger rise and fall time at the edges two PRZ pulses are generated, which lead to optical clock signal degradation. The depth of optical notch filter must be chosen proprietary.

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