Optics Communications 329 (2014) 23–27

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Optical Nyquist filters based on silicon coupled resonator optical waveguides

Ke Xu [a,*], Jiun-Yu Sung [b], Chi Yan Wong [a], Zhenzhou Cheng [a], Chi Wai Chow [b,**], Hon Ki Tsang [a]

[a] Department of Electronic Engineering, The Chinese University of Hong Kong, Shatin,N.T., Hong Kong, S.A.R
[b] Department of Photonics, National Chiao Tung University, Hsinchu 30010, Taiwan

ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form
1 May 2014
Accepted 2 May 2014
Available online 14 May 2014

Keywords:
Nyquist-WDM
Coupled resonator optical waveguide
Silicon photonics

ABSTRACT

We propose an integrated optical Nyquist filter based on silicon coupled resonator optical waveguides (CROW). The designed filter can shape the 28 Gbaud QPSK spectrum to a spectrum having 0.2 roll-off raised cosine shape with 6-dB bandwidth equals to the baud rate. The impact of the fabrication tolerance induced coupling coefficients error on the figure of merits of the filter is considered. The filter overall performance is investigated in a Nyquist-WDM system and compared with a 4th order super Gaussian filter.

1. Introduction

The continued trend of increasing demand for data transmission bandwidth has led to a revival of coherent optical communications with multi-level modulation formats [1–3] and various advanced multiplexing techniques [4–7] for enhancing the transmission capacity. Today's state-of-art complementary metal–oxide–semiconductor (CMOS) integrated circuits can enable 100 Gb/s single channel bit rate by polarization multiplexed (PM) quadrature phase-shift-keying (QPSK). Limited optical bandwidth in optical fibers has motivated interest in spectrally efficient multiplexing techniques for the next generation transmission links with terabit/s capacity. Recently, Nyquist WDM has been proposed and demonstrated with a spectral efficiency (SE) as high as 18 b/s/Hz [8]. The reported high SE is achieved by reducing the bandwidth of each channel equal to the signal baud rate with a rectangular shape which results in a near baud rate channel spacing as shown in Fig. 1(a). Ideally, the square spectrum allows for high SE with no inter-channel crosstalk as there is no channel overlap. In time domain, the corresponding sinc-like pulse transmission is expected to avoid inter-symbol interference if the signal is correctly sampled at the receiver. Compared with its counterpart—coherent optical orthogonal frequency division multiplexing (CO-OFDM)—Nyquist WDM is expected to potentially achieve the same performance but with less receiver bandwidth needed [9].

Nyquist filter either in electrical [8] or optical [10] domain is usually implemented at the transmitter. Electrical filtering is flexible and the filter profile is perfect but the maximum symbol rate is limited by the sampling speed of the state of art digital-to-analog converter (DAC) [11]. As optical filtering can avoid the limitation of electronics bandwidth, it may become the preferred approach if the desired filter shape can be easily achieved. The conventional optical filter with super Gaussian profile cannot easily approximate the required rectangular spectrum [12]. Aggressive pre-filtering is needed and can only be achieved by the programmable liquid crystal on silicon filters like the Finisar WaveShaper which is powerful but expensive and bulky. Coupled resonator optical waveguides (CROW) have been shown to be a good candidate for narrow band flat-top filter [13–15]. As single ring resonator has a Lorentz shape which limits the roll-off factor of the filter. Higher order coupled resonators could be used to shape a box-like narrow band spectrum by engineering the coupling coefficients of the CROW thus the desired impulse response may be achieved. In this paper, we proposed that CROW can be used as an optical Nyquist filter and investigate various parameters to be optimized for the filter performance. The proposed filter can be made with small size and monolithically integrated with the modulators and the multiplexers which will significantly reduce the cost.

2. Device design and analysis

The proposed filter is to be fabricated on a silicon-on-insulator (SOI) wafer with 340 nm top silicon. We consider a shallow etched waveguide with 800 nm width and 130 nm etch depth. The ring

* Corresponding author.
** Corresponding author.
E-mail addresses: kxu@ee.cuhk.edu.hk (K. Xu), cwchow@faculty.nctu.edu.tw (C.W. Chow).

http://dx.doi.org/10.1016/j.optcom.2014.05.007
0030-4018/© 2014 Elsevier B.V. All rights reserved.

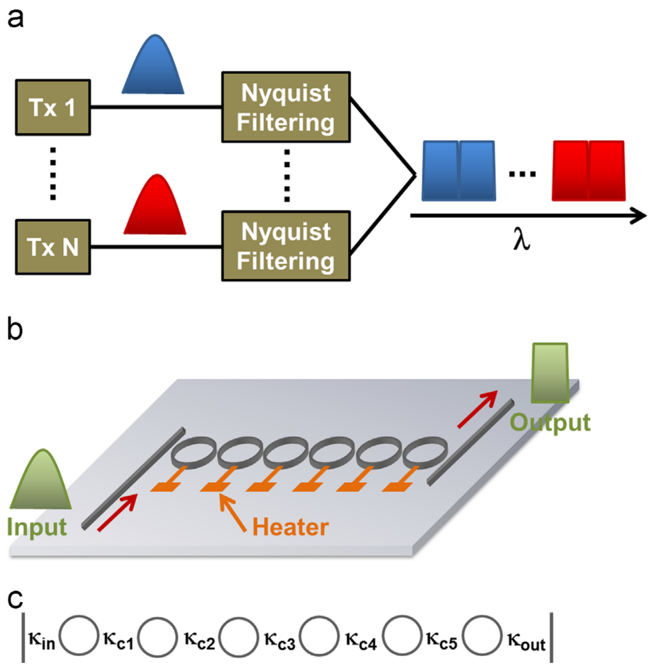

Fig. 1. (a) Illustration of the Nyquist WDM transmitter with Nyquist optical filtering elements. (b) The schematic diagram of the proposed 6th order silicon coupled resonator optical waveguides (CROW) for Nyquist optical filtering. (c) The description of the waveguide to ring and ring to ring coupling coefficients with $\kappa_{in}=\kappa_{out}$, $\kappa_{c1}=\kappa_{c5}$, and $\kappa_{c2}=\kappa_{c4}$.

radius is chosen to be 50 µm and all the ring resonators are assumed to be identical. According to 3D beam propagation simulation, the optical mode can be well confined in the waveguide with 50 µm radius with limited leakage. The waveguide loss is chosen to be 0.4 dB/cm neglecting the bending loss [16] and the wavelength dependent effective index is used for our modelling. The schematic diagram of the proposed silicon CROW is shown in Fig. 1(b). The CROW consists of two bus waveguides to couple the light in and out from a series of coupled ring resonators. Each ring is embedded with thermal heater for precise wavelength tuning. The waveguide-to-ring and ring-to-ring coupling ratios are optimized to shape the Gaussian signal spectrum to a raised cosine spectrum with a roll-off factor as low as possible while maintaining the baud rate bandwidth. All the coupling cases are considered to be lossless. The labelling of the coupling coefficients are depicted in Fig. 1(c), where κ_{in}, κ_c, κ_{out} indicate the coupling coefficients of input coupling, coupling between ring resonator and output coupling. The subscript n ($n=1, 2,\ldots 5$) is referred to the coupling between the nth and $n+1$th ring resonator. To simplify the optimization, the coupling coefficients are chosen to be symmetric: $\kappa_{in}=\kappa_{out}$, $\kappa_{c1}=\kappa_{c5}$, and $\kappa_{c2}=\kappa_{c4}$. The number of the rings should be carefully chosen to achieve a low roll-off spectrum and to reduce the tuning complexity and footprint.

The filter performance is investigated by a transfer matrix method [17]. We consider a 28 Gbaud QPSK spectrum and compare the figure of merits of the filtered spectrum for 2nd, 4th and 6th order CROW. Thus the coupling coefficients of all the three CROWs are optimized to achieve a low roll-off raised cosine like filtered spectrum with 6-dB bandwidth of 28 GHz. The phase response of the sharp edge of the filter is not included in the analysis as it can be taken care of by the digital signal processing. The filter drop port transmissions are normalized in Fig. 2(a). The dip at the center frequency is shaped by proper ring-to-ring coupling coefficients in order to flatten the Gaussian like signal spectrum. The edge of the filter becomes steeper as the number of rings increases from 2 to 6. The 6th order CROW shows a high out-of-band rejection ratio as indicated by the red solid line in Fig. 2(a). The corresponding filtered spectra of the 28 Gbaud QPSK signal are plotted in Fig. 2(b). Increasing the number of rings will steepen the roll-off. The signal spectra are shaped with roll-off factors of 0.48, 0.46 and 0.20 by 2nd, 4th and 6th order CROW, respectively. However, the filtered spectrum is still not rectangular because of the Lorentzian-like spectrum and the limited Q factor of the microring resonator. Another figure of merit is the ripple depth on top of the filtered spectrum. The ripple depths of the three CROWs are within 0.9 dB. When the number of subcarriers is small, each filtered signal may be multiplexed by optical couplers and the ripple should be small to keep the spectrum square. When there are more than 10 subcarriers, the filter can be modified to achieve a larger ripple to pre-compensate the super Gaussian like multiplexer spectrum. The insertion losses of the three CROW filters are 2.8 dB, 4.1 dB and 9.8 dB. The loss of 6th order filter is high because the filter shape requires some weak coupling between the rings. The insertion loss can be reduced by either improving the waveguide loss or modifying the coupling strength at the cost of sacrificing some of the roll-off performance. We also show the sinc-like pulse in time domain in Fig. 2(c). The signal filtered by the 6th order CROW is closest to the ideal sinc pulse because of the lowest roll-off factor.

We also study the filter performance with different ring radius. For the proposed three types of CROW, we consider the ring radius from 50 µm to 65 µm and calculate the corresponding roll-off factors and insertion losses. As shown in Fig. 3(a), the roll-off factor can be improved by using larger ring radius. For 6th order CROW, shown as the red solid line in Fig. 3(a), a roll-off factor of 0.13 can be achieved when the ring radius is 65 µm. However, the insertion loss increases significantly as the ring radius is larger, as indicated by Fig. 3(b). The insertion loss of the 6th order CROW increases by more than 10 dB with the ring radius increased from 50 µm to 65 µm. The increased loss mainly comes from the change of optimal coupling strength between the ring resonators and the increased round trip loss. Further increase the number of rings may help improve the roll-off factor of the filter but the optimization becomes more complicated, the footprint and the insertion loss increases, and the thermal tuning of individual rings becomes less practical.

Considering the fabrication tolerance, the coupling ratio of the waveguide-to-ring and ring-to-ring coupling may not be easy to make precisely. Thus we study the impact of fabricated gap distance variations corresponding to each coupling coefficient for the 6th order CROW filter. All the coupling coefficients are transferred to a more straight forward parameter (waveguide gap distance) through beam propagation simulations. The impact of the input and output coupling variation is plotted in Fig. 4(a). A small change is observed for the roll-off factor with 30 nm change in gap distance while the ripple depth has more than 3 dB variations. Compared with κ_{in}, κ_{c1} is a more sensitive parameter in terms of insertion loss as depicted in Fig. 4(b). 30 nm gap distance (κ_{c1}) variation will cause around 2 dB insertion loss difference. As gap distance increases, the ring-to-ring coupling becomes weaker, thus the insertion loss increases. Fig. 4(c) shows that κ_{c2} has a small impact on both the roll-off factor and the insertion loss. The coupling coefficient κ_{c3} is the most critical parameter in terms of the filter bandwidth, as shown in Fig. 4(d). More than 3.5 GHz bandwidth variation is caused by 30 nm gap distance change which will degrade the filter performance significantly. However, the κ_{c3} offset is not quite sensitive with regard to the roll-off factor as there is only less than 0.05 difference with the given κ_{c3} offset. It should be noted that the fabrication error of the gap distance is normally around 10 nm variation [18]. Based on the above study on the effect of each transmission coefficients, we may design the desired filter to reduce the impact of fabrication errors on filter performance.

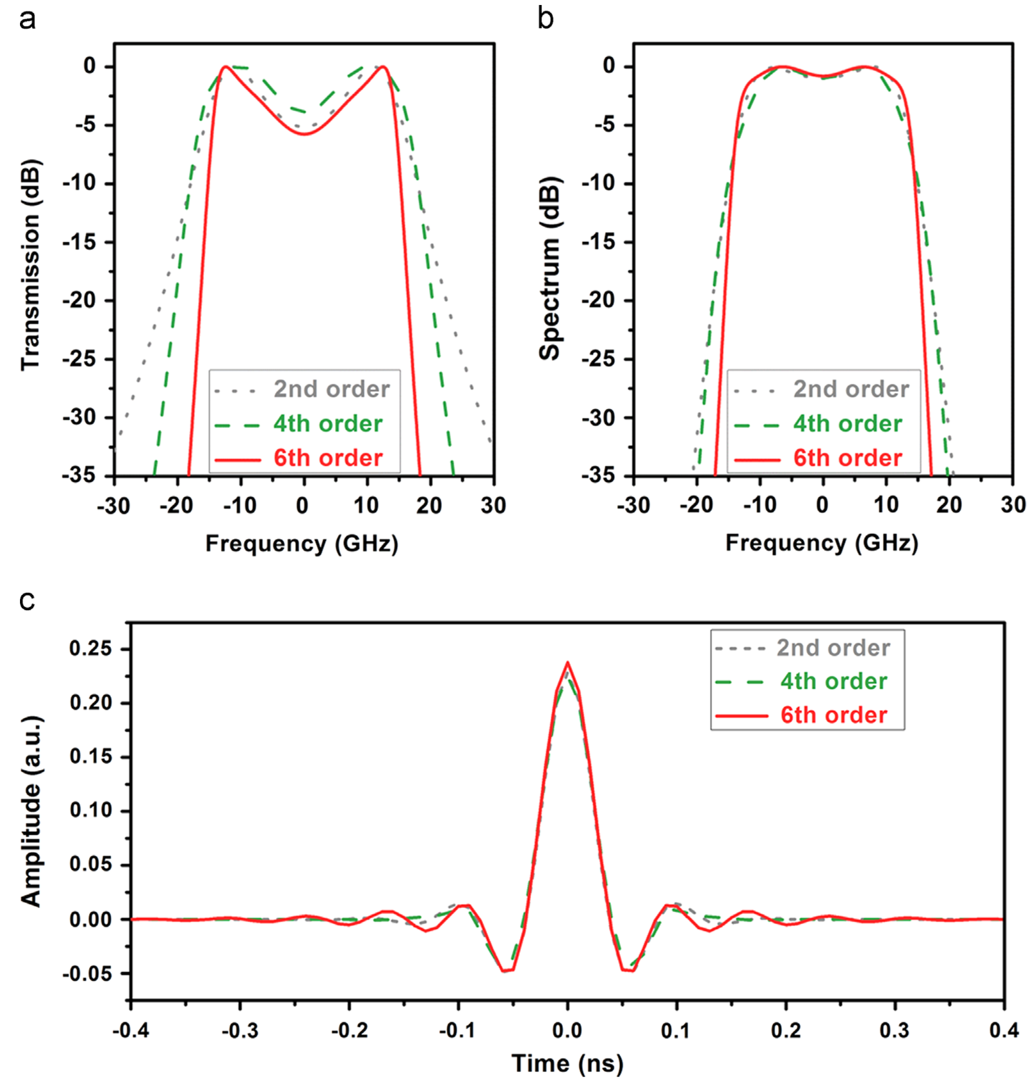

Fig. 2. (a) The normalized filter transmission of the 2nd, 4th and 6th order CROW with radius of 50 μm. (b) The corresponding raised-cosine like spectra of the filtered signals with roll-off factors of 0.48, 0.46 and 0.20. (c) The sinc-like pulse shape of the signals filtered by 2nd, 4th and 6th order CROW.

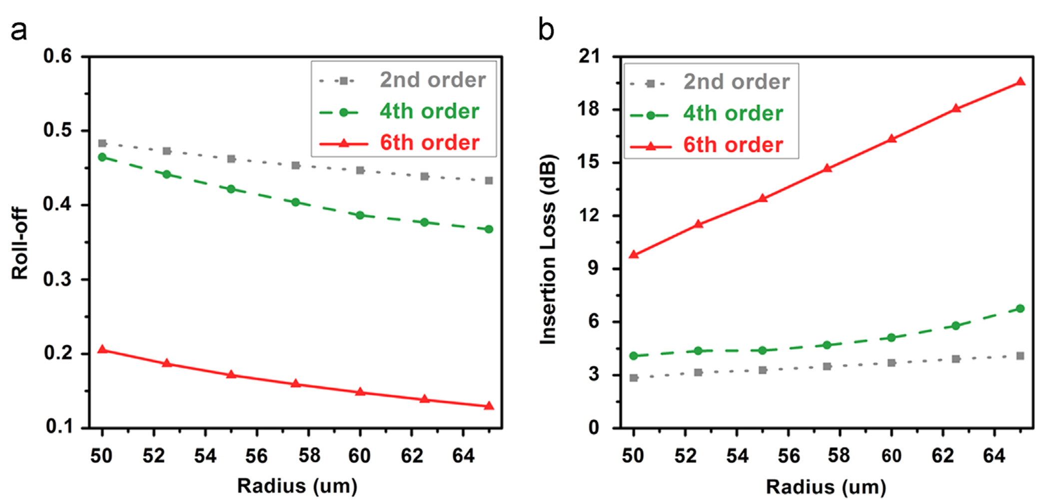

Fig. 3. (a) The roll-off factor of the filtered spectrum and (b) filter insertion loss with different ring radius of the 2nd, 4th, and 6th order CROW.

3. System investigation

We analyzed the overall performance of the silicon CROW filter by applying the designed filter to a 5-channel Nyquist-WDM system. The simulation was carried out using commercial software (VPI Transmission Maker V7.5 and MATLAB 2008a) and the system layout is depicted in Fig. 5. Each transmitter is based on an IQ-modulator driven by Rs = 28 GBaud pseudorandom binary

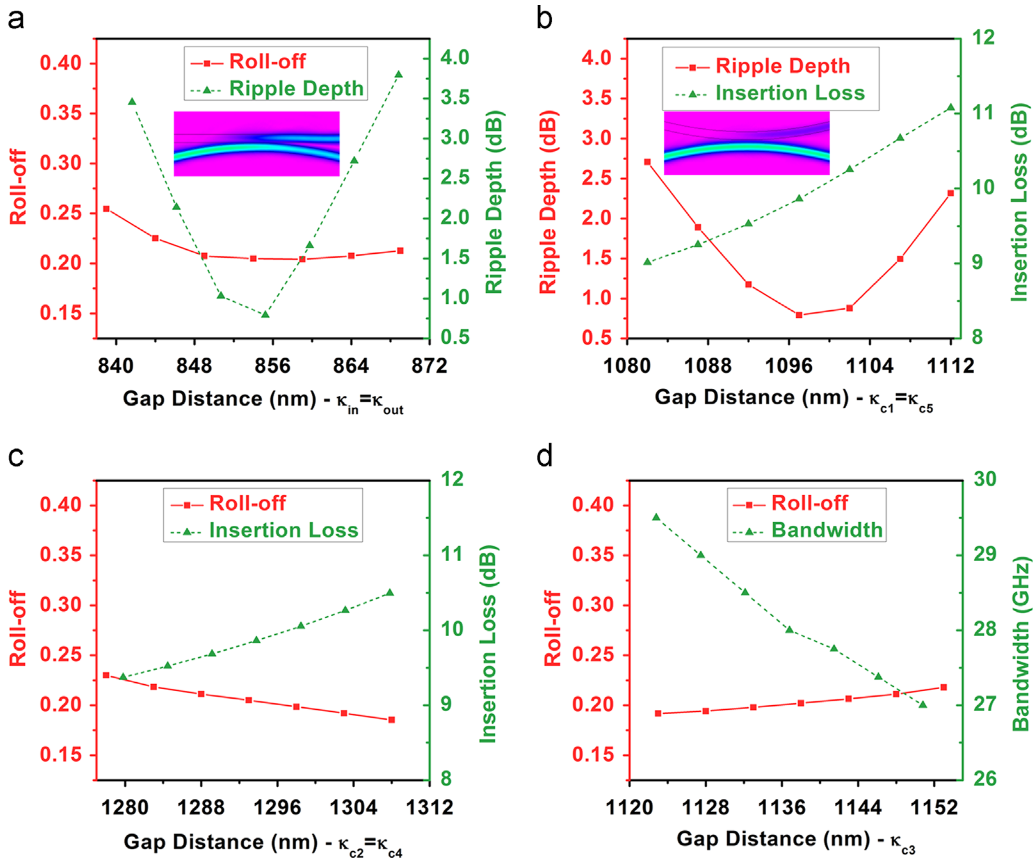

Fig. 4. (a) The roll-off factor and ripple depth as a function of the gap distance (between input/output waveguide and the ring) variation. (b) The ripple depth and filter insertion loss as a function of the gap distance between the 1st and the 2nd ring. (c) and (d) The roll-off factor and filter bandwidth as a function of the gap distance corresponding to the coupling coefficient κ_{c2} and κ_{c3}, respectively.

sequence (PRBS). The generated QPSK signal was fed into the silicon CROW filter for spectrum shaping where the operation wavelength of the CROW is tunable. The bandwidth of all the filters is chosen such that the filtered signal spectrum has a 6 dB bandwidth of Rs. All the channels were combined and the optical spectrum is shown in the inset of Fig. 5. The coherent receiver front-end consists of a local oscillator (LO) and a 90° hybrid. The laser linewidth of both the transmitter and the receiver is set to 100 kHz. Two sets of balanced photodetectors (BPDs) were used to detect the signals. The detected signals were then filtered by low-pass filters (LPFs) with bandwidth of 0.675 Rs. The signal was then sampled followed by a two-stage finite-impulse-response (FIR) equalizer.

We characterize the filter performance through back-to-back simulation. The constellations of the received signal using 2nd, 4th and 6th order CROW filter are shown in Fig. 6(a). To avoid substantial crosstalk, the channel spacing (Δf) is chosen to be 1.1 Rs and 1.15 Rs. Clear constellations can be observed for all the filters at an OSNR (over 0.1 nm) of 15 dB. The constellation with channel spacing equals to 1.1 Rs is noisier than 1.15 Rs spacing which is caused by the inter-channel crosstalk. This can be improved by using lower roll-off filter.

To further study the performance of the filter, the error vector magnitude (EVM) is estimated for the back-to-back transmission. The EVM is plotted as a function of OSNR shown in Fig. 6(b). When the channel spacing equals to 1.1 Rs, as shown by the dotted curves, sub-channel crosstalk induces a large magnitude error. For 1.15 Rs channel spacing, indicated by the solid lines, 2nd order and 4th order CROW filters have similar performance while the 6th order filter does not have a lowest EVM as expected. This is because the 6th order filter consists of 6 rings which produce

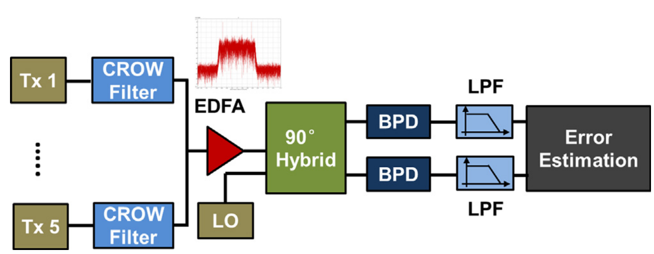

Fig. 5. Five-channel Nyquist WDM system setup for the simulation. LO: local oscillator, BPD: balanced photodetector, LPF: low-pass filter (0.67 Rs bandwidth). Inset: optical spectrum of the multiplexed signal.

larger phase shift. As the 6th order filter has the lowest roll-off factor, it should have much better performance if the phase response is compensated in the digital signal processing. As typical multiplexers have similar profile with super Gaussian (SG) function, we compare the CROW filter with the SG filter in the simulation. All the CROW filters present a much better performance than the 4th order SG filter which has a 3-dB bandwidth equals to baud rate. This is because the CROW has the potential to achieve a lower roll-off factor than conventional Gaussian filter. When the channel spacing is equal to 1.1 Rs, the 4th order CROW shows the best performance as it has a sharper edge compared with the 2nd order filter. We should point out that the EVM is large due to the inter-channel cross talk. Also, the DSP can be further optimized to improve the EVM performance and support higher level modulation format such as 16-QAM. But in this paper we focus on the feasibility of using silicon CROW as an optical Nyquist filter.

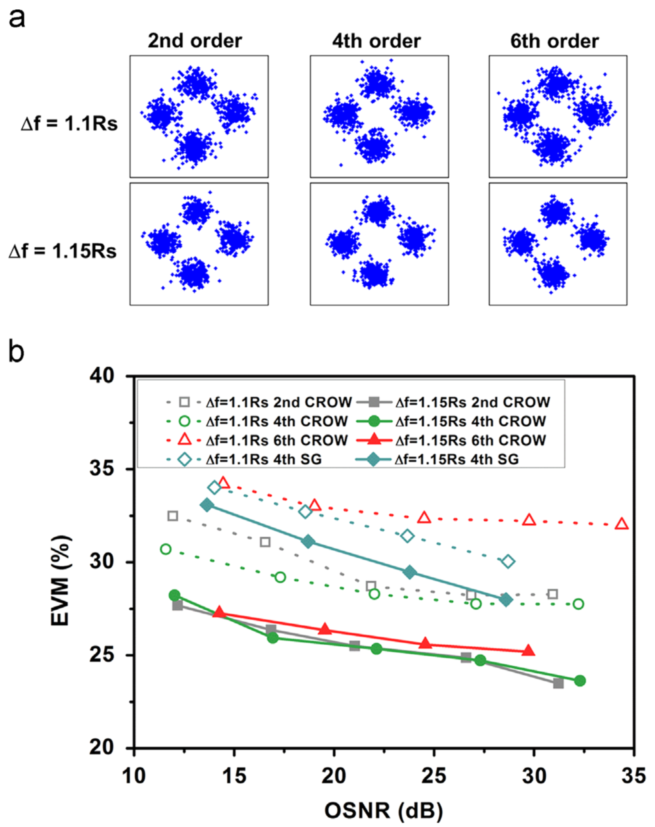

Fig. 6. (a) Constellations of the received signal at an OSNR (0.1 nm) of 15 dB. (b) The back-to-back error vector magnitude (EVM) of the received signal using various filters under channel spacing of 1.1 Rs and 1.15 Rs.

4. Conclusion

We have proposed an optical Nyquist filter based on CROW on SOI platform and investigate the performance of the filter in a Nyquist WDM system. The silicon CROW-based filter has the advantage of monolithic integration with other components such as modulators and multiplexers which may be a preferred solution in terms of the footprint and cost.

Acknowledgment

This work was supported by CUHK group research project 3110088.

References

[1] A.H. Gnauck, P.J. Winzer, S. Chandrasekhar, X. Liu, B. Zhu, and D.W. Peckham, 10 × 224-Gb/s WDM transmission of 28-Gbaud PDM 16-QAM on a 50-GHz grid over 1,200 km of fiber, in: Proceedings of the Optical Fiber Communication Conference (OFC 2010), March 21–25, 2010.

[2] X. Zhou, J. Yu, M.-F. Huang, Y. Shao, T. Wang, L. Nelson, P. Magill, M. Birk, P.I. Morel, D.W. Peckham, and R. Lingle, 64-Tb/s (640 × 107-Gb/s) PDM-36QAM transmission over 320 km using both pre- and post-transmission digital equalization, in: Proceedings of the Optical Fiber Communication Conference (OFC 2010), March 21–25, 2010.

[3] K. Xu, J.-Y. Sung, L.-G. Yang, Y.M. Chen, Z.Z. Cheng, C.W. Chow, C.H. Yeh, H.K. Tsang, J. Lightwave Technol. 31 (15) (2013) 2550.

[4] A. Sano, H. Masuda, E. Yoshida, T. Kobayashi, E. Yamada, Y. Miyamoto, F. Inuzuka, Y. Hibino, Y. Takatori, K. Hagimoto, T. Yamada, and Y. Sakamaki, 30 × 100-Gb/s all-optical OFDM transmission over 1300 km SMF with 10 ROADM nodes, in: Proceedings of the European Conference and Exposition on Optical Communications (ECOC, 2007), September 16–20, 2007.

[5] W. Shieh, X. Yi, Y. Tang, Electron. Lett. 43 (3) (2007) 183.

[6] G. Gavioli, E. Torrengo, G. Bosco, A. Carena, V. Curri, V. Migot, P. Poggiolini, M. Belmonte, F. Forghieri, C. Muzio, S. Piciaccia, A. Brinciotti, A. La Porta, C. Lezzi, S. Savory, and S. Abrate, Investigation of the impact of ultra-narrow carrier spacing on the transmission of a 10-carrier 1Tb/s superchannel, in: Proceedings of the Optical Fiber Communication Conference (OFC 2010), March 21–25, 2010.

[7] B. Zhu, T.F. Taunay, M. Fishteyn, X. Liu, S. Chandrasekhar, M.F. Yan, J.M. Fini, E. Monberg, F.V. Dimarcello, Opt. Express 19 (17) (2011) 16665.

[8] R. Schmogrow, D. Hillerkuss, S. Wolf, B. Bauerle, M. Winter, P. Kleinow, B. Nebendahl, T. Dippon, P.C. Schindler, C. Koos, W. Freud, J. Leuthold, Opt. Express 20 (3) (2012) 6439.

[9] G. Bosco, A. Carena, V. Curri, P. Poggiolini, F. Forghieri, IEEE Photonics Technol. Lett. 22 (15) (2010) 1129.

[10] J.-X. Cai, Y. Cai, C.R. Davidson, D.G. Foursa, A. Lucero, O. Sinkin, W. Patterson, A. Pilipetskii, G. Mohs, and N.S. Bergano, Transmission of 96 × 100G pre-filtered PDM-RZ-QPSK channels with 300% spectral efficiency over 10,608 km and 400% spectral efficiency over 4,368 km, in: Proceedings of the Optical Fiber Communication Conference (OFC 2010), March 21–25, 2010.

[11] G. Bosco, Spectral shaping in ultra-dense WDM systems: optical vs. electrical approaches, in: Proceedings of the Optical Fiber Communication Conference (OFC 2010), March 21–25, 2010.

[12] G. Bosco, A. Carena, V. Curri, P. Poggiolini, E. Torrengo, and F. Forghieri, Investigation on the robustness of a Nyquist-WDM terabit superchannel to transmitter and receiver non-idealities, in: Proceedings of the European Conference and Exposition on Optical Communications (ECOC, 2010), September 19–23, 2010.

[13] J.R. Ong, R. Kumar, S. Mookherjea, IEEE Photonics Technol. Lett. 25 (16) (2013) 1543.

[14] X. Luo, J. Song, S. Feng, A.W. Poon, T.-Y. liow, M. Yu, G.-Q. Lo, D.-L. Kwong, IEEE Photonics Technol. Lett. 24 (10) (2012) 821.

[15] K. Xu, C.Y. Wong, Z. Cheng, and H.K. Tsang, Performance of silicon coupled resonator waveguides for integrated Nyquist filter, in: Proceedings of the Laser and Electro-Optics Pacific Rim Conference (CLEO-PR, 2013), June 30–July 4, 2013.

[16] W. Mathlouthi, H.S. Rong, M. Paniccia, Opt. Express 16 (21) (2008) 16735.

[17] J.K.S. Poon, J. Scheuer, S. Mookherhea, G.T. Paloczi, Y.Y. Huang, A. Yariv, Opt. Express 12 (1) (2004) 90.

[18] A. Fushimi, T. Tanabe, Opt. Express 22 (4) (2014) 4466.