Multi-channel RZ to NRZ Format Conversion Based on a Single Fiber Bragg Grating

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Abstract— A multi-channel RZ-to-NRZ conversion scheme based on a single custom-designed FBG is proposed. This customized FBG is a comb filter characterized by the multi-channel reflectivity spectra. The spectral response of each channel is customized according to the optical spectra algebraic difference between the NRZ signals and the RZ signals. Simulation results show that four 200 GHz-spaced 40 Gbits/s RZ channels can be converted into NRZ signals with high Q-factor.

1. INTRODUCTION

All-optical RZ to NRZ format conversion schemes fall into two categories, namely time-domain waveform processing and frequency-domain signal spectrum tailoring [1–5]. Generally, the spectrum tailoring based converter is all-passive and very attractive compared with active-operation device [6, 7]. This is due to the advantages such as the simplicity of the structure and stable performance. However, a drawback of these devices is that they need two filters making their structure more complex [7–10].

In this work, we propose a multi-channel RZ-to-NRZ conversion scheme based on a single custom-designed FBG. This customized FBG is a comb filter characterized by the multi-channel reflectivity spectra. The only difference between the channels is their central wavelengths.

2. FBG DESIGN

The spectral response of each channel is customized according to the algebraic difference between the NRZ signals and the RZ signals. This process is described below.

As is well known, the FBG based filtering is a linear process. Thus, it's convenient to analyze the FBG based RZ to NRZ format converter with the theory of linear time-invariant system. Then, the complicated problem of converting random RZ stream to NRZ stream can be reduced to constructing an appropriate transfer function for the FBG filter based on the input spectra of RZ and the output spectra of NRZ.

In Fig. 1, we plot the spectra of RZ, the spectra of NRZ, and their algebraic difference. An interesting feature of Fig. 1 is that, although the optical spectra of the NRZ signals and the RZ signals are not smooth, their algebraic difference is quite smooth and independent of the data carried. This indicates that one can construct a transfer function based on the optical spectra algebraic difference. Since most of the NRZ signal powers are swarmed in the main lobe of the spectra (bandwidth of $|\lambda-\lambda_c| \leq \lambda_c^2/c{\cdot}T_p$) [6–11], it is reasonable to set a uniform attenuation (say, 25-dB) for out of main lobe components, and construct a band-pass filter as the spectral response of each channel. Such a well-designed single-channel spectral response is then shifted and superposed linearly to form the multi-channel reflectivity spectra. Assuming that the FBG is operated in reflection mode, mathematically, the multi-channel reflectivity spectra are written as follows:

$$r_{\mathrm{FBG,dB}}(\lambda)=\sum_{i=1}^{m} r_{i,\mathrm{dB}}(\lambda-\lambda_{c,i}),$$
$$r_{\mathrm{i,dB}}(\lambda-\lambda_{c,i})=\begin{cases}\max(n\cdot(\mathrm{FFT_{dB}}(E_{\mathrm{NRZ}}(t,\lambda_{c,i}))-\mathrm{FFT_{dB}}(E_{\mathrm{RZ}}(t,\lambda_{c,i})))\,,-25),\ |\lambda-\lambda_{c,i}|\leq\dfrac{\lambda_{c,i}^2}{c\cdot T_p}, \\ -25,\ |\lambda-\lambda_{c,i}|>\dfrac{\lambda_{c,i}^2}{c\cdot T_p}\end{cases} \tag{1}$$

where $r_{\mathrm{FBG,dB}}(\lambda)$ is the FBG multi-channel reflectivity spectra, $\lambda_{c,i}$ is the ith-channel carrier wavelength, $r_{i,\mathrm{dB}}(\lambda-\lambda_{c,i})$ is the ith-channel reflectivity spectra, m is the channel number of the FBG,

$E_{\rm RZ}(t, \lambda_{c,i})$ and $E_{\rm NRZ}(t, \lambda_{c,i})$ are the electric field of the ith-channel RZ signals and NRZ signals, respectively, 25-dB is the inter-channel isolation, T_p is the interval between pulses, c is the velocity of light in vacuum, function $\max(a, b)$ returns the largest component, FFT denotes the fast Fourier transform, and n is the filter order to be optimized according to the Q-factor of the output NRZ signals.

It should be mentioned here that the channel spacing should be chosen according to the signal bit rate. For instance, for the input RZ signals at 40-Gbit/s per channel, the channel spacing should be no less than 80 GHz. Taking into account the crosstalk between adjacent channels as well as the ITU WDM grid, we choose 200 GHz-spaced 4 channels (1546.92 nm, 1548.51 nm, 1550.12 nm, and 1551.72 nm) for the simulations. At the same time, the filter order n is optimized according to the Q-factor of the output NRZ signals, as a results, $n = 2.07$. By properly matching the FBG multi-channel reflection spectra with the spectra of the input multi-channel RZ signals, the customized FBG is well designed and synthesized using discrete layer-peeling algorithm [12].

3. SIMULATION RESULTS AND DISCUSSION

Given the 200 GHz-spaced 4 channels each operating at bit rate of 40-Gbit/s, we simulate the operation of customized FBG based optical filter for multi-channel RZ to NRZ format conversion for a pseudo-random binary sequence (PRBS) of length $2^{31} - 1$ bits. The spectra transformation is shown in Figs. 2(a) and (b). Fig. 2(a) plots the spectra of the input RZ signals before filtering, while Fig. 2(b) presents the spectra of the output NRZ signal after filtering. It is clear that the carriers which are around with strong and periodic spikes in the input RZ spectra can finely pass the FBG, while the sidebands around carriers are suppressed by the FBG. Thus the corresponding NRZ spectra are obtained via the comb filtering introduced by the proposed single FBG. In Fig. 3

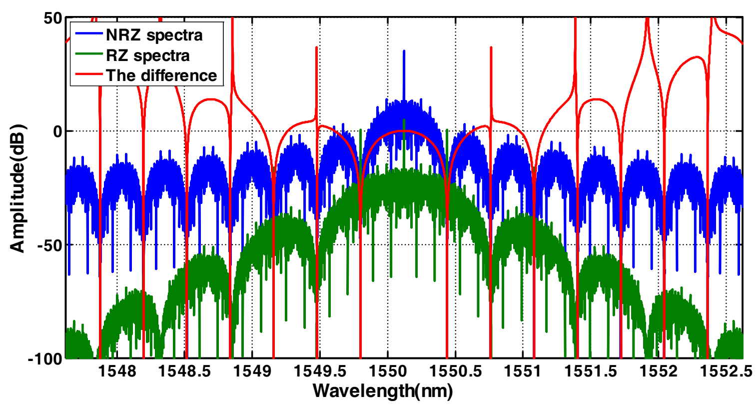

Figure 1: The spectra of the RZ signals with 50% duty cycle (the green line), the NRZ signals with $T_p = 25$ ps, the wavelength of the carrier $\lambda_c = 1550.12$ nm, and $\beta = 0.2$ (the blue line), and their algebraic difference (the ideal transfer function of the first-order filter, the red line).

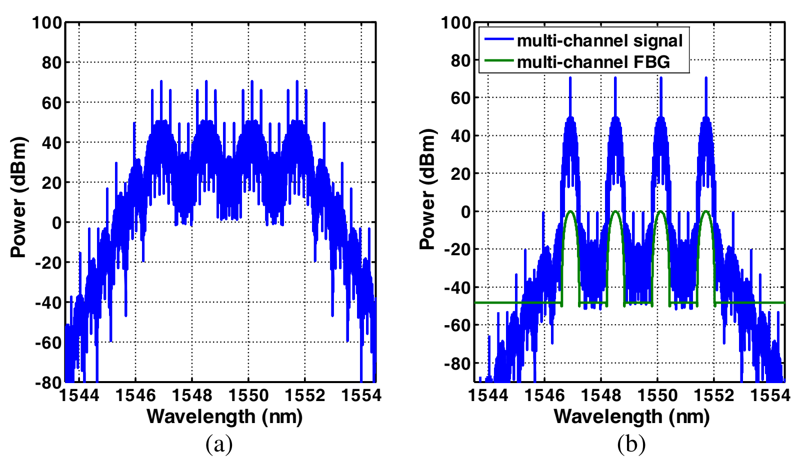

Figure 2: The spectra of (a) the 4-channel, 200 GHz-spaced input RZ signal and (b) the corresponding NRZ output.

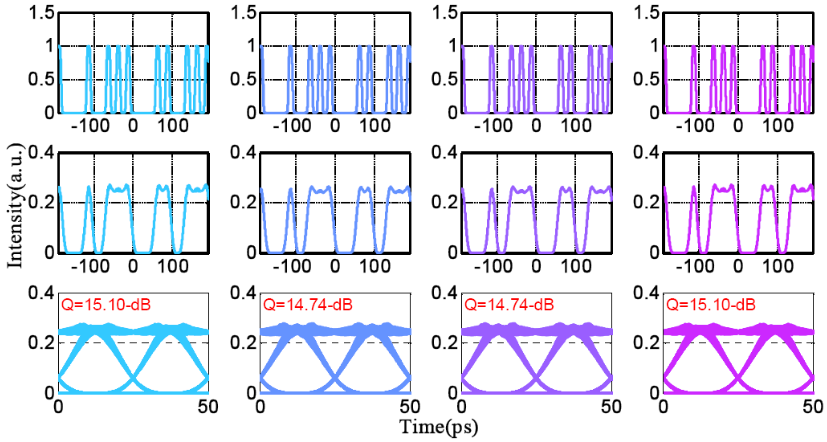

Figure 3: The input RZ waveform (the first row), the waveform and the eye diagrams for the output NRZ signals (the second row and the third row). The first column to the fourth column correspond to the carrier wavelength of 1546.92 nm, 1548.51 nm, 1550.12 nm, and 1551.72 nm, respectively (from left to right).

we plot the input RZ waveform, the waveform and the eye diagrams for the output NRZ signals. From left to right, the columns correspond to channels one to four, respectively. In the third row, the clean and open eye diagrams show that the input 4-channel RZ signals are converted to NRZ signal simultaneously with high Q-factor thanks to the all-passive scheme that introduces hardly any additional noise. The tiny decreasing of Q-factor (< 0.4-dB) in the middle channels is attributed to the residual crosstalk.

4. CONCLUSION

A single FBG based multi-channel RZ to NRZ format conversion has been proposed and simulated. Simulation results show that the customized FBG can convert 4-channel RZ signals to NRZ signals simultaneously with high Q-factor. The proposed single FBG scheme does not require any active components. It is free from any interferometric instability and ASE noise.

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REFERENCES

1. Silveira, T., A. Teixeira, G. T. Beleffi, D. Forin, P. Monteiro, H. Furukawa, et al., "All-optical conversion from RZ to NRZ using gain-clamped SOA," *IEEE Photonics Technology Letters*, Vol. 19, 357–359, 2007.
2. Yi, A.-L., L.-S. Yan, B. Luo, W. Pan, J. Ye, Z.-Y. Chen, et al., "Simultaneous all-optical RZ-to-NRZ format conversion for two tributaries in PDM signal using a single section of highly nonlinear fiber," *Optics Express*, Vol. 20, 9890–9896, 2012.
3. Du, J., Y. Dai, G. K. Lei, H. Wei, and C. Shu, "RZ-to-NRZ and NRZ-to-PRZ format conversions using a photonic crystal fiber based Mach-Zehnder interferometer," *Conference on Optical Fiber Communication (OFC), Collocated National Fiber Optic Engineers Conference, (OFC/NFOEC)*, 1–3, 2010.
4. Tang, W., M. Fok, and C. Shu, "20 Gb/s all-optical RZ to NRZ format conversion using frequency-doubling polarization-maintaining fiber loop mirror filter," *Pacific Rim Conference on Lasers and Electro-Optics, CLEO/Pacific Rim*, 1577–1578, 2005.
5. Wang, L., Y. Dai, G. K. Lei, J. Du, and C. Shu, "All-optical RZ-to-NRZ and NRZ-to-PRZ format conversions based on delay-asymmetric nonlinear loop mirror," *IEEE Photonics Technology Letters*, Vol. 23, 368–370, 2011.
6. Xiang, L., D. Gao, B. Zou, S. Hu, and X. Zhang, "Simultaneous multi-channel RZ-OOK/DPSK to NRZ-OOK/DPSK format conversion based on integrated delay interferometers and arrayed-waveguide grating," *Science China Technological Sciences*, Vol. 56, 558–562, 2013.

7. Xiong, M., O. Ozolins, Y. Ding, B. Huang, Y. An, H. Ou, et al., "Simultaneous RZ-OOK to NRZ-OOK and RZ-DPSK to NRZ-DPSK format conversion in a silicon microring resonator," *Optics Express*, Vol. 20, 27263–27272, 2012.
8. Yu, Y., Z. Xinliang, D. Huang, L. Lijun, and F. Wei, "20-Gb/s all-optical format conversions from RZ signals with different duty cycles to NRZ signals," *IEEE Photonics Technology Letters*, Vol. 19, 1027–1029, 2007.
9. Wang, F., E. Xu, Y. Yu, and Y. Zhang, "All-optical 40 Gbit/s data format conversion between RZ and NRZ using a fiber delay interferometer and a single SOA," *SPIE/OSA/IEEE Asia Communications and Photonics*, 83080E-83080E-6, 2011.
10. Yu, Y., X. Zhang, and D. Huang, "Simultaneous all-optical multi-channel RZ and CSRZ to NRZ format conversion," *Optics Communications*, Vol. 284, 129–135, 2011.
11. Ip, E. and J. M. Kahn, "Power spectra of return-to-zero optical signals," *Journal of Lightwave Technology*, Vol. 24, 1610, 2006.
12. Cao, H., J. Atai, X. Shu, and G. Chen, "Direct design of high channel-count fiber Bragg grating filters with low index modulation," *Optics Express*, Vol. 20, 12095–12110, May 21, 2012.