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# Impact of Phase-Filtering on Optical Spectral Reshaping with Microring Resonators for Directly-Modulated 4-PAM Signals

O. Ozolins<sup>1</sup>, F. Da Ros<sup>2</sup>, V. Cristofori<sup>2</sup>, X. Pang<sup>3,1</sup>, A. Udalcovs<sup>1</sup>, R. Schatz<sup>3</sup>,  
L.K. Oxenløwe<sup>2</sup>, S. Popov<sup>3</sup>, G. Jacobsen<sup>1</sup>, and C. Peucheret<sup>4</sup>

<sup>1</sup>Networking and Transmission Laboratory, RISE Acreo AB, Kista, Sweden

<sup>2</sup>DTU Fotonik, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark

<sup>3</sup>KTH Royal Institute of Technology, Kista, Sweden

<sup>4</sup>Univ Rennes, CNRS, FOTON – UMR 6082, F-22305 Lannion, France

Author e-mail address: [oskars.ozolins@ri.se](mailto:oskars.ozolins@ri.se)

**Abstract:** We investigate microring resonator (MRRs)-based optical spectral reshaping for directly-modulated 4-PAM signals. The phase-filtering of MRR, and consequent dispersion added to the signal, yields 120% reach increase compared to the 95% of amplitude-only filtering.  
**OCIS codes:** (070.2615) Frequency filtering; (200.4650) Optical interconnects

## 1. Introduction

The need for high-speed connectivity in datacenter environments is driving a significant effort in researching compact, low-cost and energy efficient solutions [1,2]. One of the proposed solutions relies on the use of directly modulated lasers (DMLs), thus replacing the need for external modulators. This choice, however, introduces the challenge of a limited transmission reach due to low dispersion tolerance and poor modulation extinction ratio (ER). These limitations may be overcome by optical spectral reshaping (OSR) by means of an optical filter, e.g an integrated microring resonator (MRR) [2]. Several demonstrations of OSR using MRRs have been reported for both on-off keying (OOK) [2,3] and 4-pulse amplitude modulation (PAM) [4,5] showing the improvement achieved in terms of reach extension. However, the impact of MRR-based filtering, in terms of the interplay between ER enhancement and added dispersion, is yet unclear. While the MRR amplitude transfer function provides frequency-to-amplitude modulation conversion, enhancing the modulation ER, its phase transfer function may provide additional narrow-band dispersion which could potentially impact the transmission reach.

In this paper we address this key aspect by a detailed numerical analysis of the OSR comparing amplitude-only and complex transfer functions (TFs) of a MRR. We show reach improvements over dispersion-uncompensated standard single-mode fiber (SSMF) links of approximately 95% thanks to optimized amplitude-only OSR for 20 GBaud 4-PAM signals. The reach is further increased up to 120% with use of the optimized complex TF.

## 2. System under investigation

Simulations (see setup Fig.1 (a)) for transmission of 20 Gbaud directly-modulated 4-PAM modulation over SSMF were performed in VPITransmissionMaker™ [6]. Two data streams generated from  $2^{15}-1$  pseudo random bit sequences with non-return-to-zero (NRZ) line coding were passively combined to create an electrical 4-PAM signal, which was applied to a directly modulated laser (DML). Single-mode laser rate equations using parameters from [7] were used. After the DML, the in-to-through TFs of an MRR were applied, either considering the amplitude-only or the full complex response. The MRR free spectral range (FSR) was set to 60 GHz and its power coupling coefficient ( $k_p$ ) was varied between 0.3 and 0.9. After photodetection, the signal was low-pass filtered with a 15 GHz 4<sup>th</sup> order Bessel filter. Error counting ( $2^{16}$  symbols) was used to calculate the bit-error-ratio (BER).

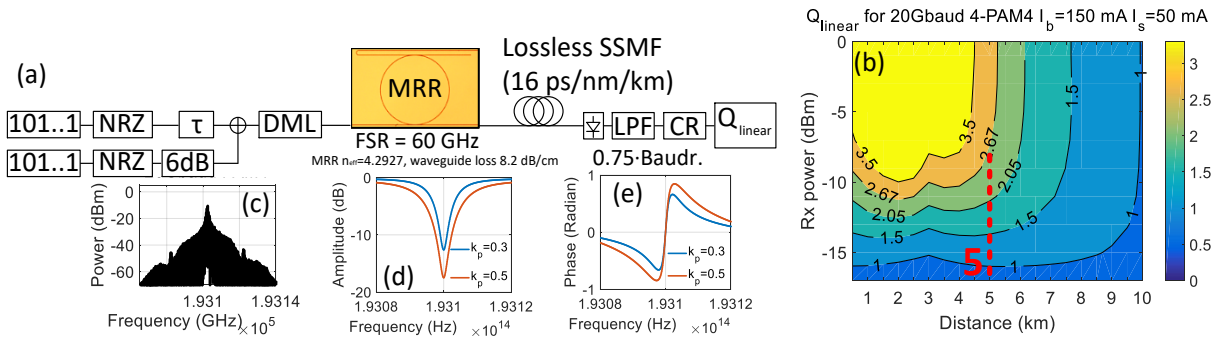


Fig. 1. (a) System under investigation; (b)  $Q_{linear}$  as a function of received power and transmission distance for 20 Gbaud 4-PAM with directly modulated laser; (c) spectrum for 20 Gbaud 4-PAM; MRR transfer function: (d) amplitude and (e) phase.

Fig. 1(b) shows the transmission reach without OSR of the 20 Gbaud 4-PAM signal with the DML biased at 150 mA and with a 50 mA modulation current swing. These biasing conditions are kept throughout the analysis. The quality factor (in linear scale,  $Q_{\text{linear}}$ ) can be calculated from the BER. The transmission reach below the 7% overhead hard-decision forward error correction (HD-FEC) threshold level of  $Q_{\text{linear}}=2.67$  ( $\text{BER}=3.8 \times 10^{-3}$ ) is approximately 5 km (0.5 km step length in simulations). The spectrum of the signal at the DML output is reported in Fig. 1(c) together with MRR transfer functions with  $k_p=0.3$  and 0.5 in Fig. 1(d) and (e), respectively.

### 3. Results and discussions

Detailed simulations were performed to investigate whether the phase transfer function of the MRR used for OSR may provide additional reach increase for the directly-modulated 4-PAM signal through partial dispersion compensation. The OSR parameters, i.e. detuning of the MRR resonance from the signal central frequency and MRR power coupling coefficient ( $k_p$ ), were optimized at a fixed MRR FSR of 60 GHz and for 5 km transmission, corresponding to the DML transmission reach without OSR. The optimization was performed for both amplitude-only and complex MRR TFs. From Fig. 2(a) it is found that the highest signal quality ( $Q_{\text{linear}}=3.6$ ) is achieved with  $k_p=0.5$  and a detuning of -6.7 GHz. With these optimized parameters, the transmission reach was investigated, as shown in Fig. 2(b). With amplitude-only OSR, the transmission reach increases to 9.5 km. The optimum frequency detuning was also checked, and it is the same for highest signal quality as in Fig. 2(a). The improvement is attributed to the frequency-to-amplitude modulation conversion that enhances the modulation ER. The same procedure (optimization of OSR and transmission reach analysis) is then repeated considering the full complex TF of the MRR. From Fig. 2(c) the highest  $Q_{\text{linear}}=3.65$  with  $k_p$  of 0.3 and a detuning of -3.3 GHz is found. Fig. 2(d) shows a transmission reach increase to 11 km. This additional reach is attributed to narrow-band dispersion introduced by the complex TF of the MRR.

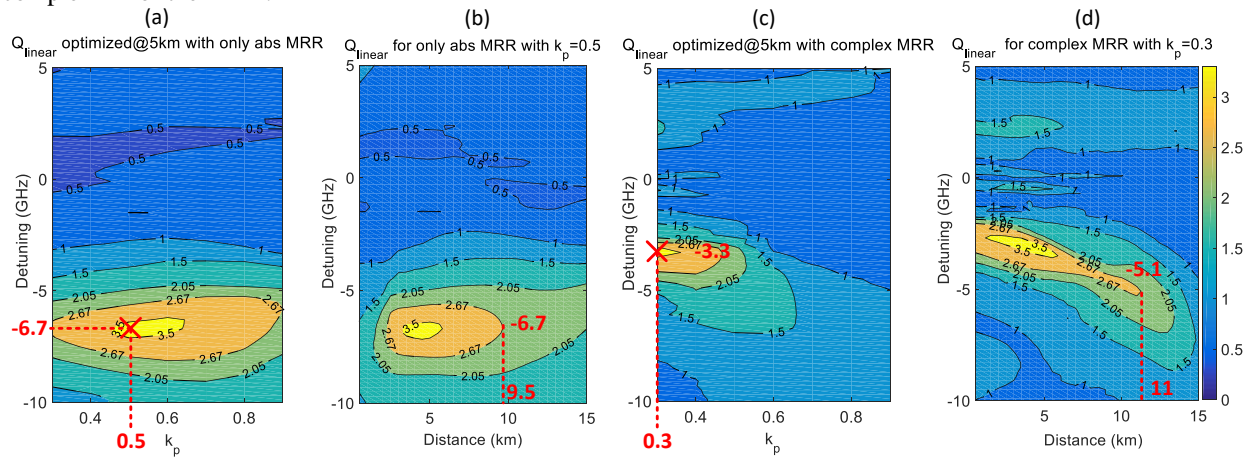


Fig. 2. (a)  $Q_{\text{linear}}$  optimization for 20 Gbaud directly-modulated 4-PAM at 5 km distance with amplitude-only TF of MRR; (b) transmission reach increase with optimized amplitude-only TF of MRR; (c)  $Q_{\text{linear}}$  optimization at 5 km distance with complex TF of MRR; (d) transmission reach increase with optimized complex TF of MRR.

### 4. Conclusions

The transmission reach enhancement is numerically demonstrated for directly-modulated 4-PAM signals using a microring resonator-based optical spectral reshaping. The contribution of the MRR phase transfer function is investigated, showing a further reach increase compared to amplitude-only filtering.

### 5. Acknowledgement

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