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*Published in:*  
I E E Photonics Technology Letters

*Link to article, DOI:*  
[10.1109/LPT.2009.2019968](https://doi.org/10.1109/LPT.2009.2019968)

*Publication date:*  
2009

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Peucheret, C., Lorenzen, M. R., Seoane, J., Noordegraaf, D., Nielsen, C. V., Grüner-Nielsen, L., & Rottwitt, K. (2009). Amplitude regeneration of RZ-DPSK signals in single-pump fiber-optic parametric amplifiers. *I E E Photonics Technology Letters*, 21(13), 872-874. <https://doi.org/10.1109/LPT.2009.2019968>

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# Amplitude Regeneration of RZ-DPSK Signals in Single-Pump Fiber-Optic Parametric Amplifiers

Christophe Peucheret, Michael Lorenzen, Jorge Seoane, Danny Noordegraaf, Carsten Vandel Nielsen, Lars Grüner-Nielsen, and Karsten Rottwitt

**Abstract**—The input power tolerance of a single-pump fiber-optic parametric amplifier (FOPA) is experimentally shown to be enhanced for return-to-zero differential phase-shift keying (RZ-DPSK) modulation compared to RZ ON-OFF keying modulation at 40 Gb/s. The improved nonlinear tolerance is exploited to demonstrate amplitude regeneration of a distorted RZ-DPSK signal in a gain-saturated FOPA. An optical signal-to-noise ratio penalty of 3.5 dB after amplitude distortion is shown to be reduced to 0.2 dB after the FOPA, thus clearly demonstrating the regenerative nature of saturated FOPAs for RZ-DPSK modulation.

**Index Terms**—Differential phase-shift keying (DPSK), fiber-optic parametric amplifier (FOPA), optical regeneration.

## I. INTRODUCTION

NONLINEAR phase noise (NPN) is one of the most severe impairments in return-to-zero differential phase-shift keying (RZ-DPSK) transmission [1]. Limiting the intensity fluctuations of the signal has been shown to reduce the accumulation of NPN, hence the need for all-optical intensity fluctuation reduction techniques that are furthermore transparent to the phase [2]. Recently, a number of techniques addressing this issue have been investigated. Those include the use of a modified nonlinear optical loop mirror with asymmetric gain profile between the counterpropagating fields [3], saturation of four-wave mixing (FWM) [2], [4], phase sensitive amplification [5], or various schemes involving phase-to-intensity modulation conversion, intensity regeneration, and phase remodulation [6].

Gain saturation in a fiber-optic parametric amplifier (FOPA) has been shown to enable intensity equalization of ON-OFF keying (OOK) signals [7]. Since the process is phase-preserving and furthermore relies on the ultrafast Kerr effect in highly nonlinear optical fibers (HNLFs), it is also expected to be suitable for amplitude regeneration of high-speed RZ-DPSK signals. Indeed, signal saturation induced by pump depletion due to FWM has been investigated numerically for DPSK signals [2]

Manuscript received October 10, 2008; revised February 24, 2009. First published April 14, 2009; current version published June 10, 2009. This work was supported in part by the European Office of Aerospace Research and Development under Grant 063094.

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Digital Object Identifier 10.1109/LPT.2009.2019968

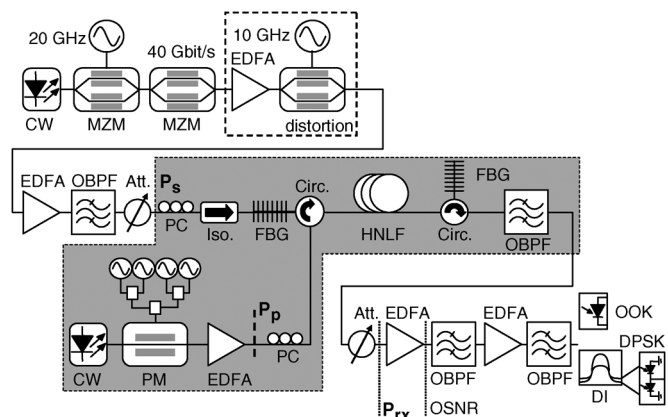


Fig. 1. Experimental setup. Att: attenuator; PC: polarization controller; Iso.: isolator; Circ: circulator; PM: phase modulator. The other acronyms are defined in the text.

and preliminary experimental results based on amplitude histograms have also been reported in the nonamplifying regime and for low duty cycle pulses [4], [8]. A recent experimental analysis of constellation diagrams in a saturated FOPA has clearly demonstrated amplitude regeneration, however, at the expense of some added phase noise [9]. Consequently, unambiguous bit-error-ratio (BER) measurements are required in order to fully assess the regenerative nature of saturated FOPAs for RZ-DPSK signals.

In this work, it is shown experimentally that the input power tolerance of a single pump (amplifying) FOPA can be significantly enhanced for RZ-DPSK modulation as compared to RZ-OOK. This effect is furthermore exploited to demonstrate successful amplitude regeneration of a highly distorted 40-Gb/s RZ-DPSK signal in an FOPA with over 20-dB small signal gain. This letter complements the results recently presented in [10].

## II. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 1. A 40-Gb/s 33% RZ-OOK or RZ-DPSK signal is generated from a continuous-wave (CW) laser using a Mach-Zehnder modulator (MZM) pulse carver driven by a 20-GHz sinusoidal signal followed by a data modulator driven with a  $2^{31} - 1$  pseudorandom binary sequence (PRBS). The modulation format is selected by a proper choice of the bias and peak-to-peak voltage of the data signal applied to the second MZM. The signal input power to the FOPA is then adjusted using an erbium-doped fiber amplifier (EDFA) followed by an optical bandpass filter (OBPF) and a variable attenuator. The pump signal is derived from a CW laser amplified up to 30.5 dBm in an EDFA. In order

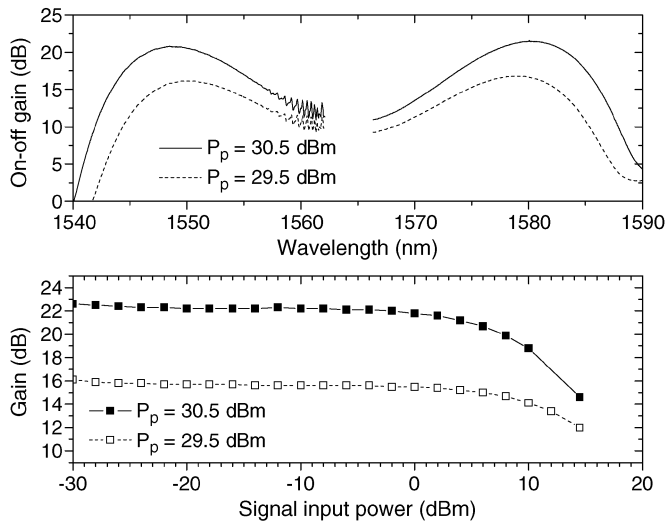


Fig. 2. FOPA ON-OFF gain spectrum (top) and gain as a function of signal input power (bottom).

to suppress stimulated Brillouin scattering (SBS), the pump is phase modulated using four sinusoidal tones at 123, 600, 1000, and 2350 MHz. The SBS threshold of the fiber, estimated at 17 dBm without phase modulation, could be increased beyond 28 dBm using the four modulating tones. Signal and pump are coupled into the 500-m-long highly nonlinear fiber using a fiber Bragg grating (FBG) and a circulator. This coupling scheme also enables reduction of the amplified spontaneous emission (ASE) noise generated in the high-power EDFA used to amplify the output of the pump laser. The HNLf has zero dispersion at 1560.5 nm, a dispersion slope equal to  $0.015$  ps/(nm<sup>2</sup> · km), an attenuation of 0.74 dB/km, and a nonlinear coefficient of  $11.5$  W<sup>-1</sup> · km<sup>-1</sup>. At the HNLf output, the signal wavelength is selected using another FBG followed by an OBPF, with full-width half-maximum bandwidths of 1.4 and 1.3 nm, respectively. The signal is then input to a receiver consisting of an optical preamplifier and a 40-GHz photodiode (in the case of OOK) or a 1-bit delay interferometer (DI) followed by a balanced detector (in the case of DPSK).

### III. RESULTS AND DISCUSSION

The FOPA was characterized for a pump wavelength of 1564.1 nm and a CW signal, as shown in Fig. 2. The ON-OFF gain, defined as the ratio of the signal power at the HNLf output with the pump turned ON to the same quantity with the pump turned OFF, peaks around 1549.5 and 1548.5 nm for 29.5- and 30.5-dBm pump power, respectively. Due to the availability of an FBG at that wavelength, the signal was tuned to 1546 nm in the experiments. The FOPA exhibits clear saturation behavior with small signal gains of 16 and 22 dB and input saturation powers of 13 and 9.5 dBm for 29.5- and 30.5-dBm pump power, respectively. Once saturation, a prerequisite for amplitude regeneration, is clearly established under static operation, the FOPA performance can be evaluated for modulated signals.

The optical signal-to-noise ratio (OSNR) penalty compared to back-to-back was measured (in a 0.1 nm bandwidth) at a BER of  $10^{-9}$  as a function of signal input power to the FOPA for both RZ-OOK and RZ-DPSK modulation. The limitation of the performance of the amplifier by poor OSNR and nonlinearities at low and high input power, respectively, is clearly observed

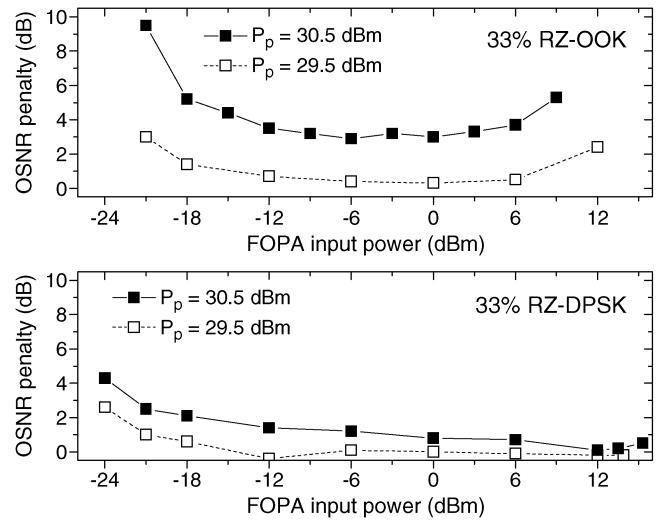


Fig. 3. OSNR penalty as a function of FOPA input signal power for RZ-OOK (top) and RZ-DPSK (bottom) modulation.

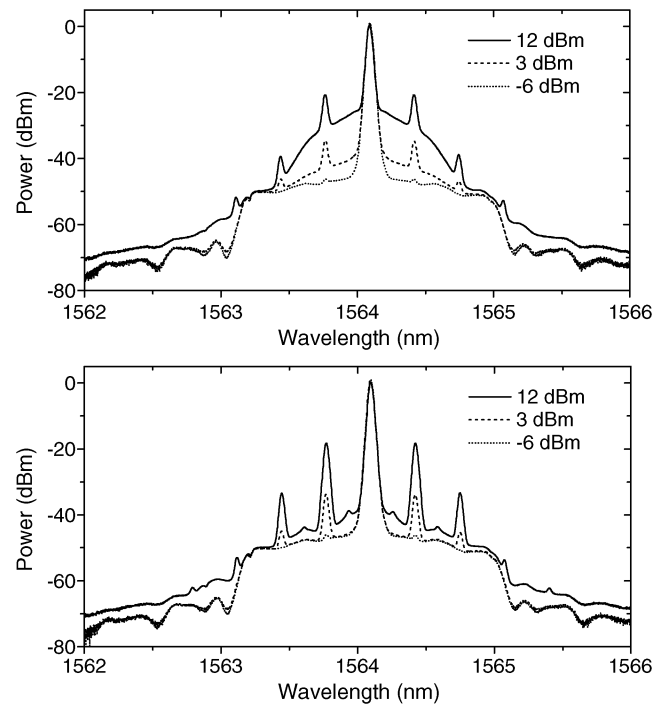


Fig. 4. Spectra in the vicinity of the pump wavelength in the case of RZ-OOK (top) and RZ-DPSK (bottom) modulation.

in Fig. 3 in the case of RZ-OOK. The higher penalty observed for 30.5-dBm pump power is due to enhanced self-phase modulation (SPM) at high path average power through the HNLf. However, the inherent resilience of RZ-DPSK to SPM, which is due to its periodic power envelope, results in lower penalty and larger high input power tolerance than for RZ-OOK. Such an observation is in line with recent studies dealing with double pump FOPAs [11]. The onset of nonlinear degradation had actually not been reached with the maximum value of signal power that was available in our experiment (15 dBm).

Fig. 4 compares the spectra in the vicinity of the pump wavelength for RZ-OOK and RZ-DPSK and for signal input power to the FOPA of -6, 3, and 12 dBm. The effect of cross-phase

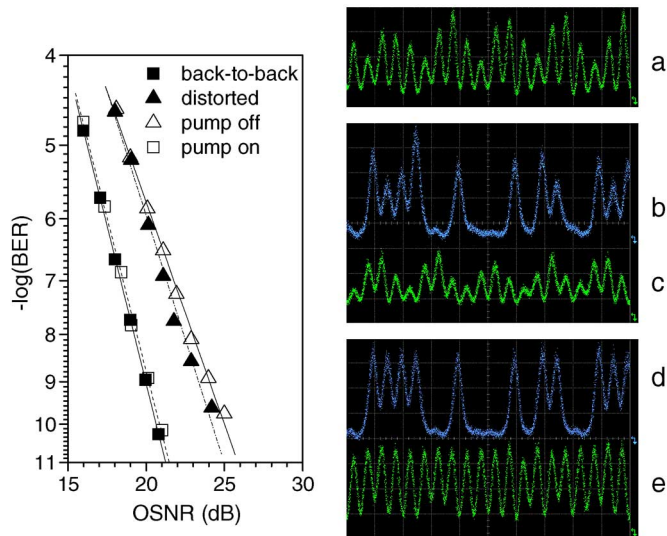


Fig. 5. BER curves and patterns for RZ-DPSK (a) after distortion; (b), (c) at FOPA output with pump OFF; (d), (e) at FOPA output with pump ON. (a), (c), and (e) correspond to RZ-DPSK intensity waveforms, while (b) and (d) are the corresponding waveforms after the DI and single-ended detection.

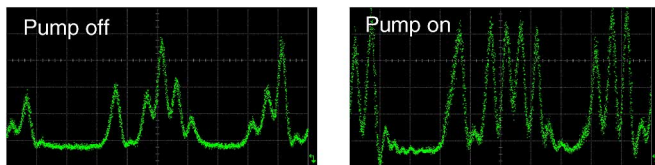


Fig. 6. RZ-OOK waveforms at the FOPA output with the pump turned OFF (left) and ON (right).

modulation from the signal to the pump is clearly visible for high input signal power and reflects the nature—pseudorandom versus periodic—of the power envelope of the signal.

The enhanced dynamic range is exploited to demonstrate amplitude regeneration of an RZ-DPSK signal. For this purpose, an extra MZM driven by a 10-GHz sinusoidal signal is used to emulate the intensity fluctuations that would result from transmission over an optical fiber link. The distorted signal is input to the FOPA with 13.4-dBm average power in order to experience gain saturation. The distorted input signal is shown in Fig. 5(a). This distortion results in 3.5-dB penalty compared to a back-to-back undistorted RZ-DPSK signal and 4.1-dB penalty after propagation through the FOPA with the pump turned OFF. The optical waveform and the single-ended detected signal after demodulation (Fig. 5(c) and (b), respectively) clearly show severe intensity fluctuations. However, when the 30.5-dBm pump is turned ON, those amplitude fluctuations are suppressed [Fig. 5(d), (e)]. Accordingly, the penalty after the FOPA is reduced to 0.2 dB, clearly demonstrating its regenerative behavior.

Amplitude equalization of RZ-OOK was also attempted with the same amount of intensity distortion and the same FOPA pump power. The waveforms at the FOPA output with the pump turned ON and OFF are shown in Fig. 6. The intensity of the signal was partly equalized owing to FOPA saturation for 13.2-dBm

input power. However, at this power level, the high SPM degradation prevented error-free detection of the signal, as anticipated from the input power tolerance investigation reported in Fig. 3 for an undistorted signal. For 10-dBm average power, corresponding to the same peak power as for RZ-DPSK, only incomplete equalization was observed. Even though saturation may be obtained with lower pump and signal power, one important requirement for a practical amplitude regenerator is that it provides a sufficiently high output signal power and OSNR, which may not be met with conventional nonamplifying FWM configurations. The FOPA thus provides a unique combination of gain and saturation.

#### IV. CONCLUSION

It has been shown that single-pump FOPAs offer an increased input power dynamic range for RZ-DPSK modulation compared to RZ-OOK. This behavior can be exploited to achieve intensity regeneration of RZ-DPSK signals in an FOPA with 22-dB gain, without being limited by SPM, as would be the case for RZ-OOK. The first unambiguous BER characterization of an FOPA-based regenerator for amplitude equalization of 40-Gb/s RZ-DPSK signals was also presented.

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