

# Amplification of WDM Signals in Fiber-Based Optical Parametric Amplifiers

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**Abstract**—We demonstrate for the first time, experimentally, the performance of fiber-based optical parametric amplifiers in wavelength-division-multiplexed (WDM) applications. Both a  $3 \times 10$  Gb/s and a commercial  $7 \times 2.5$  Gb/s WDM system are investigated together with the parametric amplifier. Limitations due to pump depletion and four-wave mixing are quantified. Measurements showing the performance in terms of power penalty and gain versus input–output signal power are presented.

**Index Terms**—Four-wave mixing (FWM), highly nonlinear fiber (HNLF), optical parametric amplifier, wavelength-division multiplexing (WDM).

## I. INTRODUCTION

FIBER-BASED optical parametric amplifiers (FOPAs) have been successfully used both as pulse sources [1] and as amplifiers with high net gain and with sensitivity comparable with Erbium-doped fiber amplifiers (EDFAs) [2]. Recently, a tunable and high-power return-to-zero pulse source for wavelength-division-multiplexed (WDM) systems based on FOPA with sinusoidally modulated pump was presented [3]. A very interesting question is, thus, whether the FOPA also can be used as an amplifier in WDM systems. In this study we show, to our knowledge, the first experimental results of a continuous-wave (CW) pumped FOPA and its performance as an amplifier for WDM systems. Results are presented for different amplifier gain and signal power in terms of power penalty for both a  $3 \times 10$  Gb/s and a  $7 \times 2.5$  Gb/s WDM system. Limiting effects such as cross-gain saturation (XGS) due to pump depletion and four-wave mixing (FWM) are quantified.

## II. EXPERIMENTAL PRINCIPLE

The experimental setup of the FOPA and the WDM source is shown in Fig. 1. Uncorrelated 10-Gb/s pseudorandom binary sequences (PRBS) nonreturn-to-zero data with word-length  $2^{31} - 1$  was applied on each WDM channel originating from the three external cavity lasers (ECL1, ECL2, ECL3). Note that while different PRBS data were applied on each WDM channel, the bit slots were synchronized, i.e., the copropagating bits of different channels overlapped in time. The polarization

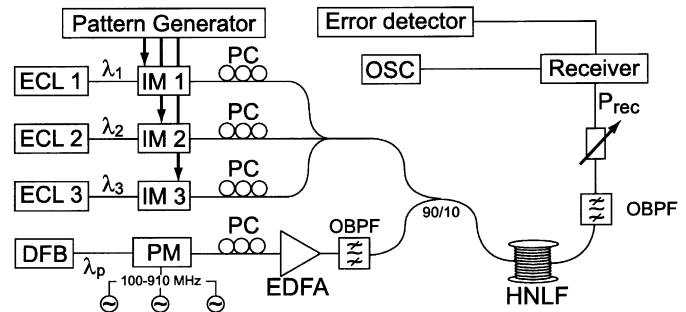


Fig. 1. Experimental setup. IM: intensity modulator. OSC: oscilloscope. OBPF: optical bandpass filter.

states of the three channels were aligned with polarization controllers (PCs) to the same state of polarization, combined and launched into the FOPA. The distributed feedback (DFB) laser light at 1562.7 nm was amplified in a high-power EDFA and served as pump for the FOPA. In order to suppress the stimulated Brillouin scattering, the pump was phase modulated (PM) with three RF signals (100, 310, and 910 MHz) [4]. The WDM channels were combined together with the pump signal through a 10-dB coupler into a 500-m dispersion-shifted highly nonlinear fiber (HNLF), which had a nonlinear coefficient  $\gamma = 12 \text{ W}^{-1}\text{km}^{-1}$ , an effective core area  $A_{\text{eff}} = 12 \mu\text{m}^2$ , a zero-dispersion wavelength  $\lambda_0 = 1560.4 \text{ nm}$ , a dispersion slope of  $0.03 \text{ ps/nm}^2\text{km}$ , and a fiber loss of  $0.7 \text{ dB/km}$ . The experimental setup also consisted of an EDFA preamplified receiver with an optical filter bandwidth of  $1.3 \text{ nm}$  and an electrical detector bandwidth of either 10 or 2.5 GHz. The bit-error rate (BER) was measured as a function of received power ( $P_{\text{rec}}$ ). In particular, the system performance in terms of receiver sensitivity at  $\text{BER} = 10^{-9}$  was quantified. This setup was used to evaluate the performance of the FOPA when inserting one, two, or three WDM channels at 10 Gb/s into the FOPA. A similar configuration was later used for the evaluation of the commercial 2.5-Gb/s WDM system where up to seven channels were amplified in the FOPA.

## III. XGS AND FWM

In transmission systems, it is required that the optical data stream experiences the same gain, regardless of being “0” or “1.” Due to pump depletion, the gain of the FOPA saturates instantaneously for high input signal peak powers. This means that the gain saturates not only as an average, like in an EDFA with significantly longer gain saturation time constant ( $\sim 10 \text{ ms}$ ), but on a bit level, which for example can result in that a “1” experiences less gain than a “0.” This effect is even more distinct in a WDM system since the total input signal power to the

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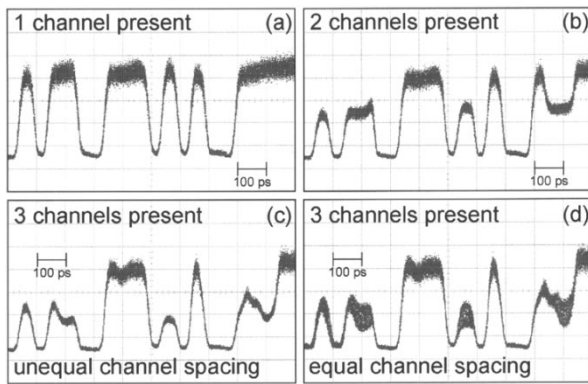


Fig. 2. Oscilloscope traces showing how a 10-Gb/s bit sequence on Channel 1 is deteriorated by XGS and FWM from adjacent WDM channels. (a) Unaffected channel. (b) Two channels present. (c) Three channels present with unequal channel spacing. (d) Equal channel spacing. Small signal gain = 24 dB, Input signal power = -16 dBm.

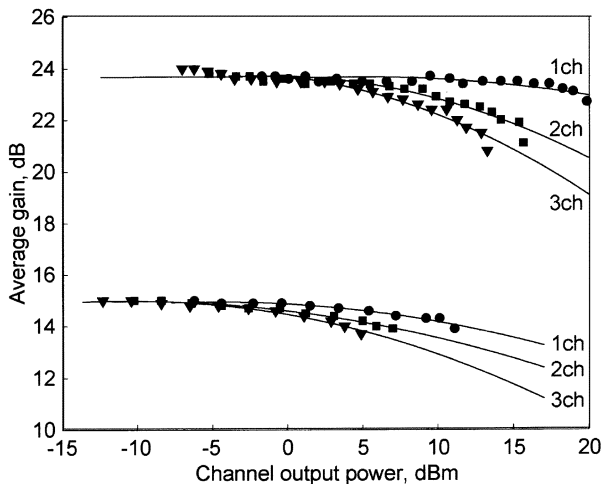


Fig. 3. Gain versus channel output power for one, two, and three channels present with 15- and 24-dB small-signal gain.

FOPA varies substantially and saturates the gain at high input power, which leads to the effect of XGS, i.e., the input power of one channel saturates the gain of another channel. Fig. 2(a) shows a typical unaffected pattern on Channel 1 after 24-dB amplification and approximately 8-dBm channel output power. If two channels are present, the gain instantaneously saturates (by approximately 2.4 dB) when the two sequences have overlapping one-bits, as shown in Fig. 2(b). This effect is even more detrimental when three channels are simultaneously amplified (approximately 4.7-dB saturation when all three channels have overlapping one-bits), as shown in Fig. 2(c) (unequal channel spacing), while FWM manifests as an increased intensity noise that appears in Fig. 2(d) (equal channel spacing). The unequal channel spacing is accomplished by a slight detuning in wavelength for one of the channels.

Fig. 3 shows the average gain for two different pump powers, 31 and 32 dBm, corresponding to two different small-signal gain levels, 15 and 24 dB. The gain was calculated excluding the 10-dB signal loss in the coupler. Note that this loss could be omitted, e.g., by using a WDM interleaver. The gain saturates with increasing signal power and with the number of channels. Note that, e.g., a 3-dB saturation of the average gain (i.e., the

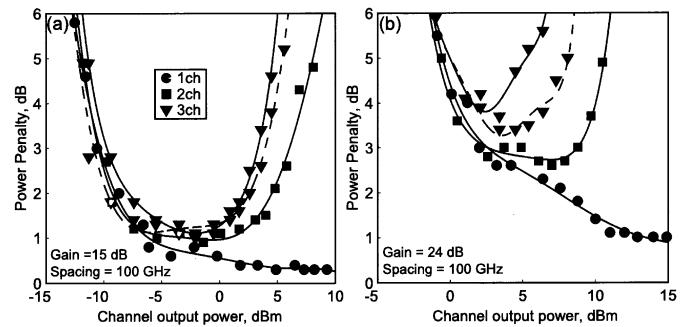


Fig. 4. Power penalties versus channel output power with one, two, and three channels present for (a) 15- and (b) 24-dB gain at 100-GHz spacing. Dashed line shows three channels with unequal channel spacing.

channel average output power divided by the channel average input power) in Fig. 3 corresponds to more than 3-dB local gain saturation in Fig. 2, which leads to significant eye closure or power penalty even at 1-dB average gain saturation. The effects of XGS could, in principle, be suppressed by using gain clamping [5], i.e., to combine CW light with high power together with the data channels. By placing this signal at a wavelength that is of no interest for data transmission, the variations due to pump depletion could be decreased. The problem of XGS and the gain clamping principle has been used for semiconductor optical amplifiers [6]. FWM will also deteriorate the data since the signals themselves will act as pumps and create new wavelengths [7]. When inserting more channels into the FOPA, the XGS effect will, however, dominate since this depends on the total signal power, i.e., all channels. The FWM mostly affects adjacent channels since the FWM crosstalk bandwidth only will be a fraction of the total gain bandwidth, a fraction that decreases when the distance between the signal and the zero dispersion wavelength increases [7].

#### IV. RESULTS—POWER PENALTY

One output signal (Channel 1 at  $\lambda_1 = 1544.81$ ) from the FOPA was then filtered out and sent into the EDFA preamplified receiver. The receiver sensitivity at BER =  $10^{-9}$  was measured and the power penalty was calculated in relation to the -34-dBm sensitivity back-to-back without the FOPA. The power penalty was measured for the two gain levels (15 and 24 dB) as a function of signal power and with one, two, and three channels present for 100- and 200-GHz spacing. The results from the 100-GHz case ( $\lambda_1 = 1544.81$  nm,  $\lambda_2 = 1545.61$  nm, and  $\lambda_3 = 1546.40$  nm) are shown in Fig. 4. At low input power levels, the optical signal-to-noise ratio (OSNR) at the FOPA output limits the performance, and the penalty is comparable for identical input power levels independent of the gain and the number of channels. At high power levels, channel interaction from XGS and FWM induces a penalty. However, the latter only occurs when more than two channels are present. The differences between 100- and 200-GHz spacing are small and depend also on where the signal wavelengths are located in the FOPA gain spectrum. As discussed above, the penalty from FWM is caused by the appearance of an idler wave from two signals at the same wavelength as the third. This effect can, thereby, be removed if the signal wavelengths are carefully chosen, and

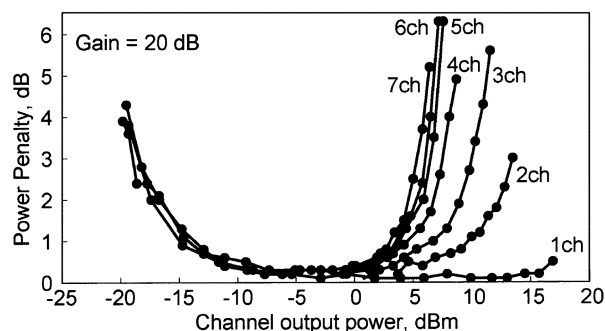


Fig. 5. Power penalty versus channel output power (ITU Channel 4) for one and up to seven channels present using a commercial 2.5-Gb/s WDM system with 100-GHz channel spacing.

in Fig. 4, the dashed lines show the penalty when one of the wavelengths are detuned (typically more than 10 GHz, i.e., the electrical receiver bandwidth) resulting in an unequal channel spacing. In this case, the penalty from FWM in a three-channel WDM system is removed. The maximum channel power with three channels present and a power penalty less than 3 dB is approximately 2.5 dBm at 15-dB gain. When the small-signal gain was increased to 24 dB, a power penalty less than 3 dB was not achievable for three channels. This is due to the fact that the two regions (low input power where the performance is limited by OSNR, and high output power where the performances is limited by FWM and XGS) are overlapped.

## V. WDM-FOPA IN COMMERCIAL SYSTEMS

A commercial 2.5-Gb/s WDM-system (Ericsson, Erion Networker) was used to investigate the effects of multiple channels using an FOPA as an inline amplifier. As before, the polarization states of the seven channels (ITU Channels 1–7) were aligned to the same state with PCs, combined, and launched into the FOPA.

The penalty was measured in the same way as before and is shown in Fig. 5 for ITU Channel 4 ( $\lambda = 1549.32$  nm) for an FOPA gain of 20 dB. The receiver sensitivity was  $-43$  dBm back-to-back without the FOPA. As before, the OSNR limits the performance for low input powers, while XGS and FWM limits the performance for high input powers and increasing number of channels. From the results in Fig. 5, we can see that the maximum output power per channel with seven channels present and a power penalty less than 3 dB is approximately 5 dBm. Comparing Figs. 4 and 5, it is apparent that the maximum output power is larger for the 2.5-Gb/s system. This is explained by the fact that the bit slots in this case, compared with the 10-Gb/s three-channel case, were not synchronized in time so that the XGS effect to some extent was averaged out for a large number of channels. A typical spectrum (channel output power  $\sim -5$  dBm) after the HNLf in the FOPA is shown in Fig. 6. The spectrum shows the seven channels (100-GHz channel spacing), the pump, and the generated idlers at longer wavelengths.

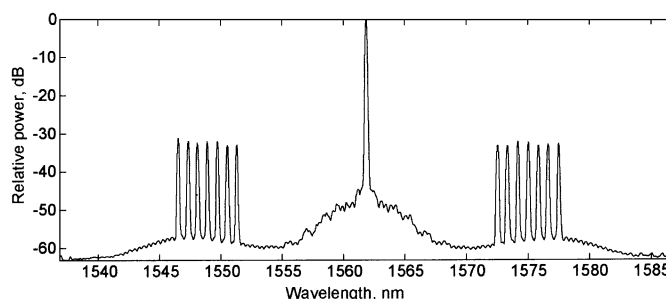


Fig. 6. Spectrum after the HNLf in the FOPA with seven input signals.

## VI. CONCLUSION

We have presented, to our knowledge, the first experimental results on FOPA as amplifier for WDM systems. We have found impairments from both XGS and FWM, limiting the performance of the FOPA; however, the effects from FWM were reduced by unequal channel spacing. The effects of FWM could, in principle, also be reduced by, e.g., using orthogonal polarization on adjacent channels in a polarization insensitive FOPA, whereas the effects of XGS could be reduced by using gain clamping. Due to the very short gain saturation time constant in the FOPA compared with, e.g., an EDFA, the gain saturates on a bit-level time constant, which leads to the XGS effect. This effect will limit the performance of the FOPA when the number of channels increase since it depends on the total signal power, i.e., all channels. The FWM mostly affects adjacent channels since the crosstalk bandwidth only will be a fraction of the total gain spectrum, a fraction that will decrease with the signal distance to the zero dispersion wavelength. Other effects that can limit the performance, such as self-phase modulation and cross-phase modulation, need to be investigated further.

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