Power consumption and FWM crosstalk analysis of a hybrid S-band amplifier based on two parametric wavelength converters and an EDFA

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Abstract: We measure and analyze the power efficiency and four-wave-mixing crosstalk of a hybrid S-band amplifier based on parametric wavelength converters and EDFA at input signal levels from –30 to –20 dBm/ch and 20-dB gain.

1. Introduction

The fast exponential growth of data traffic [1] demands higher and higher optical transport capacities, while the capacity of the conventional C and L bands is already approaching the Shannon limit owing to the use of advanced modulation formats, probabilistic shaping, and digital signal processing. Exploring the bands outside of erbium-doped amplifier (EDFA) bandwidth, and in particular the neighboring S-band [2], is hence very attractive for meeting the growth demands. The existing S-band amplification solutions, however, are far from ideal: thulium-doped fiber amplifiers have splicing issues and require auxiliary pumps, while fiber Raman amplifiers and optical parametric amplifiers (OPAs) have pump efficiencies that are significantly lower than EDFA's, and their high-gain regimes suffer from various impairments, such as double Rayleigh backscattering, pump relative intensity noise transfer, stimulated Brillouin scattering (SBS), four-wave mixing (FWM), etc. Thus, a hybrid S-band amplifier employing two OPA-based wavelength converters and an EDFA between them [3] can be a very attractive alternative to these approaches. It can use OPAs with low gains, thereby avoiding high-gain-related issues of the OPA and shifting the burden of generating high gain to a power-efficient EDFA. We have numerically optimized [4] and experimentally confirmed [5] the low (4.5–5.5 dB) noise figure (NF) of the hybrid S-band amplifier, and demonstrated this amplifier's suitability for 16-QAM-modulated WDM signals [6]. The amplified WDM spectrum has exhibited the presence of four-wave-mixing crosstalk (FWM Xtalk) generated in the highly-nonlinear fiber (HNLF), which could be suppressed by assigning more gain to (i.e., reducing signal power at the input of) the last wavelength conversion stage. Since such FWM mitigation approach would require more OPA pump power, there is going to be a trade-off between the power consumption and FWM Xtalk suppression, and the optimum balance between them will depend on the signal output power.

In this paper, we experimentally investigate both pump power consumption and FWM Xtalk in the hybrid S-band amplifier with high (–20 dBm/ch), medium (–25dBm/ch) and low (–30dBm/ch) signal input powers. We fix the conversion efficiency (CE) of the first wavelength conversion stage at +8 dB and the total gain of the hybrid amplifier at 20 dB, while varying the gain splitting between the EDFA and the second wavelength conversion stage.

2. Hybrid S-band amplifier and experimental setup for its characterization

The schematic of hybrid S-band amplifier is shown in Fig. 1. The amplifier consists of 3 stages. In the first stage, OPA-I serves as a wavelength converter to convert the S-band signal to L-band idler. The converted L-band idler is filtered out using an optical tunable filter (OTF) and amplified by the L-band EDFA (stage 2). In the third stage, the amplified L-band idler serves as a signal for the second wavelength converter OPA-II and is converted back to S-band. Finally, the amplified S-band signal is filtered out with another OTF to realize the S-band amplification. The SBS-suppressing phase modulation of the pump is initially imprinted onto the idler beam by OPA-I and then is subsequently removed by OPA-II after synchronizing the pump phase modulation patterns at the inputs of OPA-I and OPA-II by adjusting the clock rate of the modulation pattern (for more information, see [5]). We use 500-m-long HNLF for OPA-I and 200-m-long HNLF for OPA-II. Both fibers have zero-dispersion wavelength of 1551.5 nm and nonlinear constant γ = 21.4/W/km. The hybrid amplifier's output is characterized by an optical spectrum analyzer (OSA).

To analyze the power consumption and FWM Xtalk of the hybrid S-band amplifier, we use the input signal consisting of 8 WDM channels with 100-GHz spacing [6] and obtain data at three input power levels representing high (–20 dBm/ch), medium (–25 dBm/ch), and low (–30 dBm/ch) power. The criteria used to estimate the power consumption is the total pump power used by OPA-I, OPA-II and middle L-band EDFA to generate 20 dB total gain.

According to the NF analysis in [4], the NF of the hybrid amplifier is largely determined by the CE of stage 1. Hence, we keep the OPA-I CE at +8 dB (first stage pump power of 25 dBm), which generates a decent NF < 6 dB [5]. We raise the L-band EDFA's pump power and reduce the pump power of OPA-II stage (and vice versa) to maintain the 20 dB total gain. In the characterization of amplified spectrum, the FWM Xtalk is read by turning off channel 4 in the middle of the WDM channel plan, measuring the optical power of the FWM tone at the position of this channel, and dividing it by the power of the signal channel. The optical signal-to-noise ratio (OSNR) is obtained by dividing the signal channel power by the amplified spontaneous emission (ASE) noise power within the OSA resolution bandwidth of 0.067 nm. The total signal-to-noise ratio (SNR) is calculated as the ratio between the amplified signal power and the total power of the FWM tone and ASE noise within 0.067 nm.

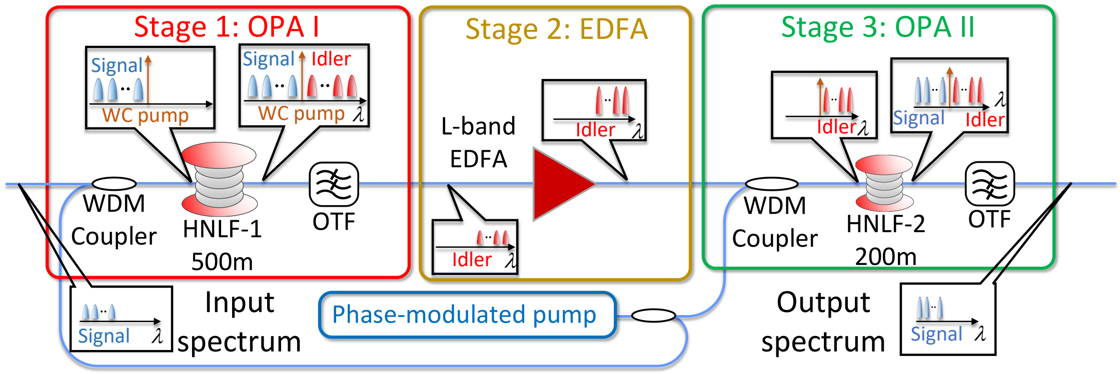

Fig. 1. Schematic of the hybrid S-band amplifier. EDFA: erbium-doped fiber amplifier; HNLF: highly-nonlinear fiber; OPA: optical parametric amplifier; OTF: optical tunable filter; WC: wavelength conversion; WDM: wavelength-division-multiplexer.

3. Results and discussion

The OSNRs and inverse FWM crosstalks (–Xtalk in dBs) are summarized in Fig. 2 for three input power levels. For high input power level (and, consequently, high output power level), the total SNR and –Xtalk curves coincide, indicating that the total SNR is determined by the FWM Xtalk.

At low input power, the total SNR is determined by the OSNR.

At medium input power, when the pump power in OPA-II stage is lower than 24.2 dBm, FWM Xtalk is the dominant noise; for pump power between 24.2 and 24.8 dBm, the noise contributions from ASE and FWM are on same scale; and when the pump power is above 24.8 dBm, the ASE is the dominant noise source. For low OPA-II pump power, the last-stage CE is low, which forces the L-band amplifier to generate strong L-band signal going into HNLF-2, which causes high FWM Xtalk. At high OPA-II pump powers the CE is high, and the L-band EDFA power going into HNLF-2 is low, which reduces the Xtalk. These observations give guidance on how to choose OPA-II pump power to get an optimal total SNR for the hybrid S-band amplifier.

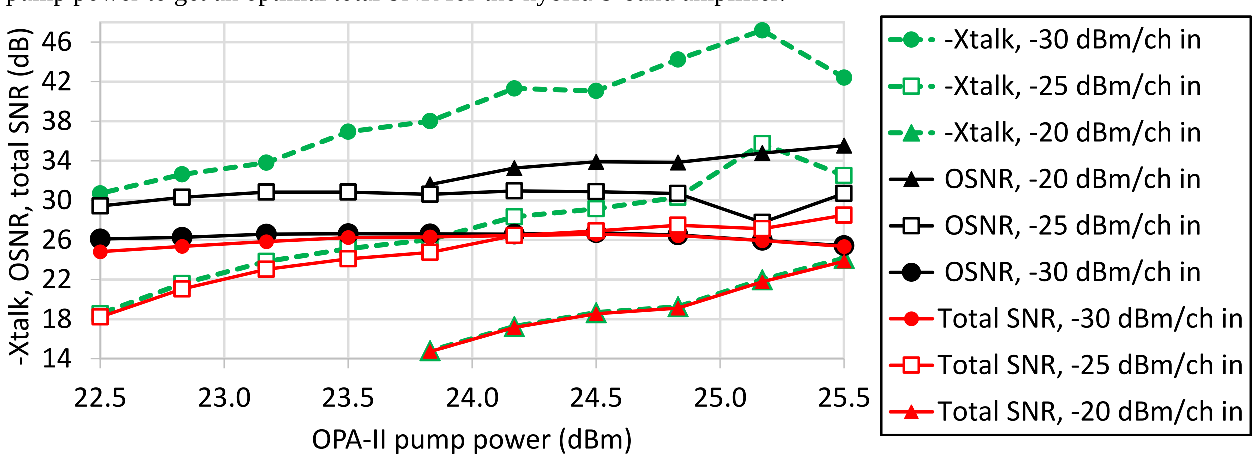

Fig. 2. Inverse FWM crosstalk (–Xtalk, green), OSNR (black), and total SNR (red) for three input power levels (filled circles for –30 dBm/ch, empty squares for –25 dBm/ch, filled triangles for –20 dBm/ch) vs. the OPA-II pump power at fixed 20 dB total gain.

We combine the curves of the total SNR and pump power consumption versus OPA-II pump power in Fig.3. For low input power, the minimum power consumption and maximum total SNR are achieved when OPA-II pump power is equal to 23.5 dBm. Since FWM Xtalk for low input power is very low, the total SNR stays almost constant when the OPA-II pump power increases. At the same time, the power consumption increases, because unsaturated (linear) L-band EDFA is more power efficient than OPA-II.

For medium input power, the total SNR monotonically increases with the OPA-II pump power, because the resulting higher CE of OPA-II leads to lower FWM Xtalk. The total pump power varies very little for OPA-II powers at or below 24.5 dBm. Above this point, the total SNR improvement occurs at the expense of higher power consumption.

For high input power, it is interesting to observe that the CE increase in OPA-II stage by increasing its pump power results in both power savings and performance improvement. High CE not only reduces the FWM Xtalk, but also improves the power efficiency, because the saturation of the L-band EDFA at these signal levels makes it less efficient compared to the OPA-II.

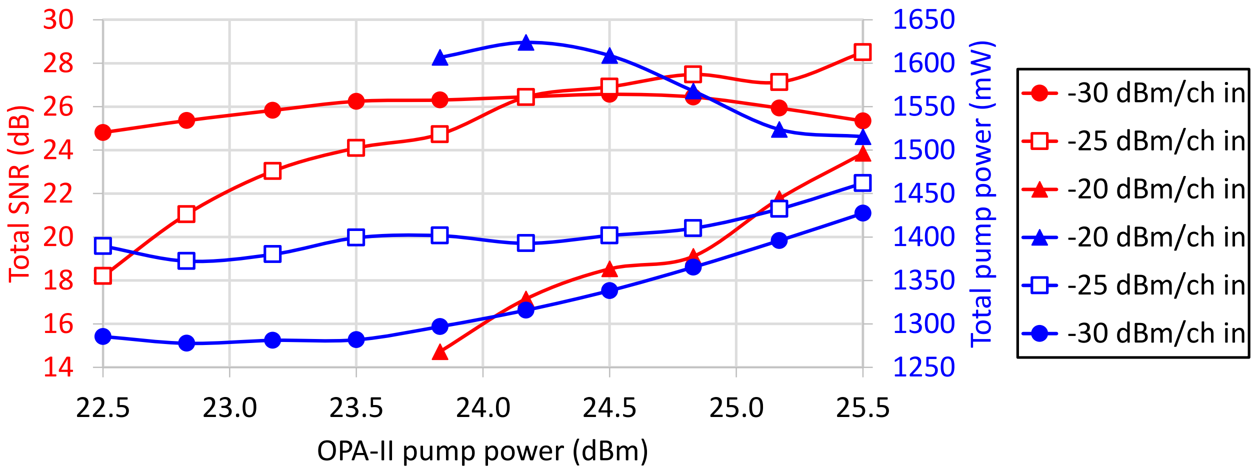

Fig. 3. Total SNR (red, left scale) and total pump power (blue, right scale) for three input power levels (filled circles for –30 dBm/ch, empty squares for –25 dBm/ch, filled triangles for –20 dBm/ch) vs. the OPA-II pump power at fixed 20 dB total gain.

4. Conclusions

We have analyzed the role of FWM crosstalk in hybrid S-band amplifier by comparing the contribution of FWM and ASE noise to the total SNR. The crosstalk is the dominant noise for high input signal power levels, while the ASE noise is the dominant noise for low input signal power levels. The power consumption at high input signal power can be reduced by generating higher wavelength conversion efficiency in OPA-II. For medium input power, power consumption and signal performance monotonically improve with increasing OPA-II pump power. For low input signal power, an optimal OPA-II pump power can be found, which achieves highest total SNR while keeping the power consumption at a minimum. This information helps to optimize practical hybrid S-band amplifier and make it suitable for possible deployment in optical transport networks.

5. Acknowledgement.

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6. References

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