Investigation of Hybrid S-band Amplifier Performance with 8-channel × 10 Gbaud 16-QAM signals

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Abstract *We experimentally demonstrate a hybrid S-band amplifier, consisting of two parametric-amplifier-based wavelength converters and an L-band EDFA in the middle, and evaluate its performance with 8 WDM channels carrying 10 Gbaud 16-QAM data.*

Introduction

The use of advanced modulation formats and digital signal processing technology is rapidly bringing the transmission capacity of C- and L-band close to its Shannon limit. The most obvious way to further increase the transmission capacity is to extend optical communications to S-band. This, however, so far has been impeded by the inadequacy of existing S-band amplifiers: thulium-doped fiber amplifiers exhibit high noise figure (NF)[1] due to high splicing loss between fluoride and silica fiber; fiber Raman and parametric amplifiers have poor pump efficiencies, as well as performance issues at high gains, such as double Rayleigh backscattering noise[2] in Raman amplifiers and stimulted Brillouin scattering (SBS) and relative intensity noise (RIN) transfer of the pump in parametric amplifiers.

Recently, we proposed a hybrid S-band amplifier that consists of two wavelength conversion stages based on optical parametric amplifiiers (OPAs) and an L-band EDFA as the middle stage.[3] Here, compared to a stand-alone high-gain fiber OPA, the burden of providing large gain falls onto the EDFA, which has low noise figure and excellent pump efficiency, whereas a pair of OPA wavelength converters serve as bridges between S-band and either C- or L-band. To achive best total NF, the first OPA needs to have moderate 6–10 dB conversion efficiency (CE), while the second OPA only needs CE near 0 dB.[4] This hybrid approach both improves the pump efficiency and avoids nonlinear degradations of high-gain OPAs. We have analyzed[4] and characterized[5] the NF of the hybrid amplifier, but the measured NF did not include the effects of pump RIN transfer and signal nonlinearities. In this paper, we characterize the performance of the S-band hybrid amplifier with all impairments included by studying it with 8 wavelength-division multiplexed (WDM) channels modulated by 10 Gbaud 16-QAM data.

Experimental setup

Our experimental setup is shown in Fig. 1. At the input of hybrid amplifier, eight S-band channels with 50-GHz spacing (1527.44–1530.14 nm) are aligned in their polarization states, combined by 1×8 optical coupler, and modulated by 10 Gbaud 16-QAM data. They are subsequently sent

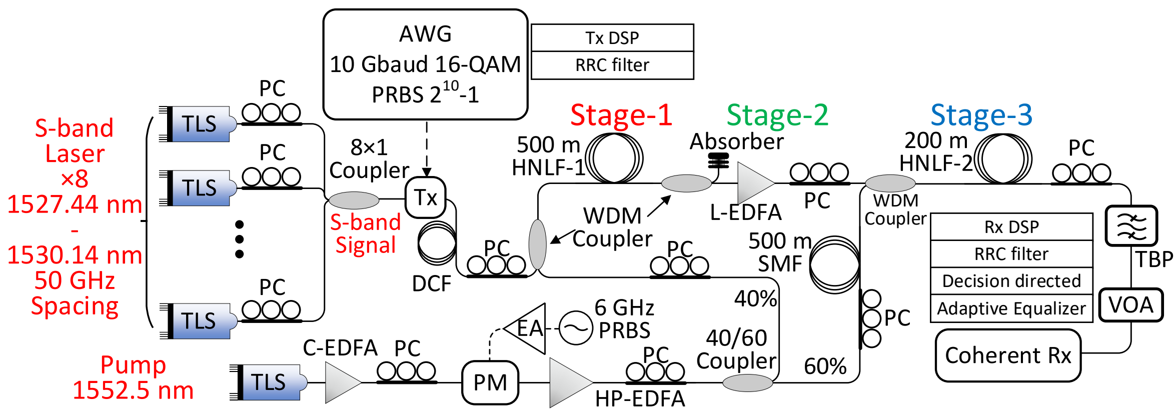

Fig. 1: Experimental setup. AWG: Arbitrary waveform generator; C-EDFA: C-band erbium-doped fiber amplifier; DCF: Dispersion compensating fiber; DSP: Digital signal processing; EA: electrical amplifier; HNLF: highly-nonlinear fiber; L-EDFA: L-band erbium-doped fiber amplifier (EDFA); HP-EDFA: high-power EDFA; OSA: optical spectrum analyzer; PC: polarization controller; PM: phase modulator; PRBS: pseudorandom bit sequence; Rx: Receiver; SMF: single-mode fiber; VOA: variable optical attenuator; TBPF: Tunable bandpass filter; TLS: tunable laser source; Tx: Transmitter; WDM: wavelength-division multiplexing.

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through a dispersion compensation fiber (DCF) with –356 ps/nm dispersion to decorrelate the patterns among the adjacent channels by 1.4 symbols to enable more accurate evaluation of the nonlinear degradations. To avoid SBS, the 1552.5-nm pump used for the two OPA wavelength converters (stage 1, or OPA-I, and stage 3, or OPA-II) is BPSK-modulated with 6 Gbps pseudo-random bit sequence (PRBS), with clock rate fine-tuned to make the difference between the signal/pump delays at OPA-I and OPA-II inputs a multiple of the pump PRBS pattern length. This setting ensures that the phase modulation transferred to the idler in OPA-I is perfectly cancelled by OPA-II, yielding no trace of pump modulation in the S-band output. At the input of OPA-I, the WDM signals are combined with 40% of pump power (377 mW) by a WDM coupler and sent through 500-m-long highly nonlinear fiber (HNLF from Furukawa) with zero dispersion wavelength of 1551.5 nm and nonlinear constant γ = 21.4/W/km for conversion of S-band signals to L-band idlers. After OPA-I, the L-band idler beams are filtered out by a WDM coupler and fed into an L-band EDFA, while the residual pump power is absorbed by a fiber-optic light trap at the other output port of the WDM coupler. The amplified idlers after L-band EDFA are combined with 60% of pump power (556 mW) that has been delayed by a 500-m-long single-mode fiber (SMF) to reduce the difference between signal/pump delays at the inputs of stages 1 and 3. The amplified L-band idlers are converted back to S-band in OPA-II, whose HNLF has the same properties as the first HNLF, but has a shorter 200-m length. Among the output (amplified) S-band signals, we select one channel by a tunable optical bandpass filter to be sent to a coherent receiver (IQS70 by Coherent Solutions) and measured by a real-time oscilloscope (LeCroy LabMaster 10-65Zi-A).

Experimental results

The input and output spectra of the hybrid amplifier and middle-stage L-band EDFA are shown in Fig. 2. The total gain is in the 25.8…27.1-dB range for all 8 channels. The previously characterized total NFs yielded 4.6…5.6-dB values for the range of our signal wavelengths.[5]

We characterize the overall performance of the hybrid S-band amplifier by measuring 3 representative channels (#3, #5, and #8) among the 8 WDM channels. Their 16-QAM constellations at the hybrid S-band amplifier output are shown in Fig. 3(c,f,i). One can see that the outer constellation points exhibit some nonlinear distortion due to self-phase modulation in OPA-II, indicating that the OPA-II is better suited for output powers that are lower than approximately –1 dBm / channel obtained in our setup.

The error vector magnitudes (EVMs) and bit error ratios (BERs) of the characterized channels are also summarized in Fig. 3. The BERs of all output signals are below the soft-decision FEC threshold of 1.5×10^{-2}. The power penalties compared to the back-to-back (B2B) case are roughly commensurate with the combination of the effective loss (difference between the B2B power and the input powers of the hybrid amplifier, which are –29.1, –26.5, and –27.2 dBm for channels 3, 5, and 8, respectively) and the S-band amplifier NF (4.6…5.6 dB).

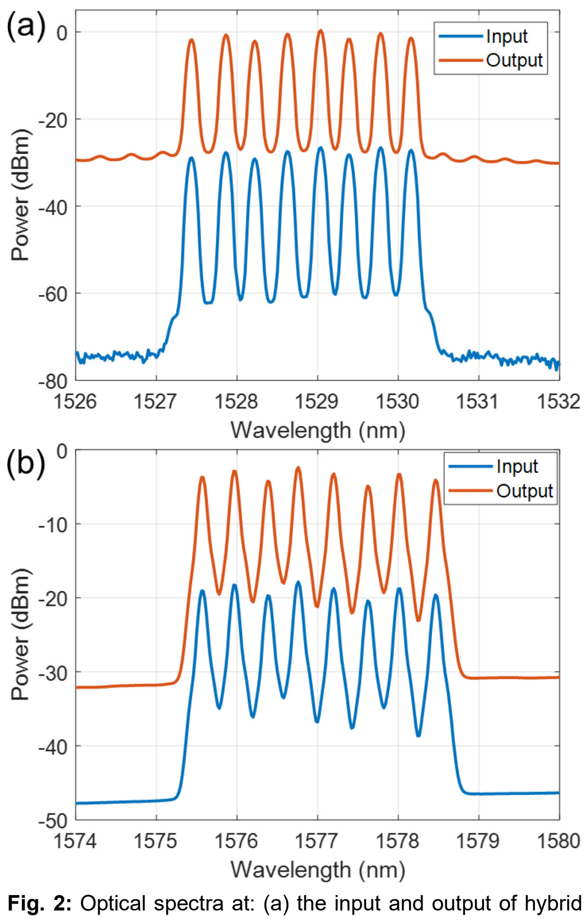

Fig. 2: Optical spectra at: (a) the input and output of hybrid amplifer; (b) the input and output of L-band EDFA (stage 2).

Conclusions

We have experimentally verified 16-QAM performance of a hybrid S-band amplifier consisting of two wavelength converters and an L-band EDFA at the middle stage. All measured channels have BERs below the soft-decision FEC threshold and power penalties roughly commensurate with the combination of pre-amplification loss and NF of the hybrid amplifier. At –1-dBm / channel output, some amount of nonlinear distortion is also observable in the constellation diagrams, which suggests that the amplifier output power needs to be reduced for optimum performance. The observed results indicate the viability of the hybrid amplifier as a solution for S-band amplification.

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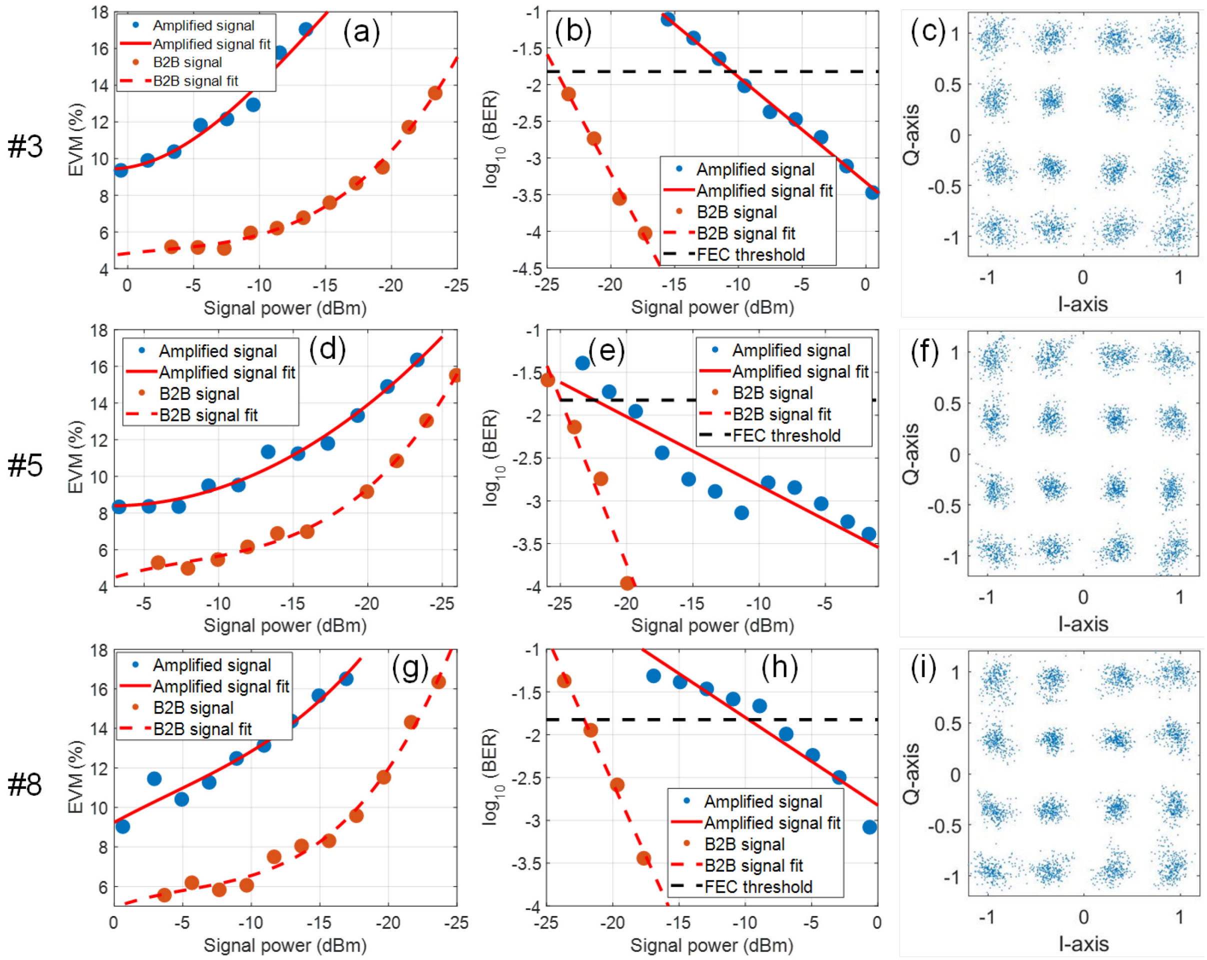

Fig. 3: Error vector magnitudes (EVMs) of channels #3 (a), #5 (d), and #8 (g). Bit-error ratios (BERs) of channels #3 (b), #5 (e), and #8 (h). 16-QAM contellations at the S-band hybrid amplifier output for channels #3 (c), #5 (f) and #8 (i).