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Experimental Investigation of a Hybrid S-Band Amplifier Based on Two Parametric Wavelength Converters and an Erbium-Doped Fiber Amplifier

Cheng Guo ¹ , Afshin Shamsschooli ¹ , Michael Vasilyev ^{1,*} , Youichi Akasaka ², Paparao Palacharla ², Ryuichi Sugizaki ³ and Shigehiro Takasaka ³

¹ Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019, USA; cheng.guo@mavs.uta.edu (C.G.)

² Advanced Technology Labs, Fujitsu Network Communications, Richardson, TX 75082, USA

³ Furukawa Electric Company Ltd., Ichihara 290-8555, Japan; shigehiro.takasaka@furukawaelectric.com (S.T.)

* Correspondence: vasilyev@uta.edu

Abstract: Multi-band optical communication presents a promising avenue for the significant enhancement of fiber-optic transmission capacity without incurring additional costs related to new cable deployment via the utilization of the bandwidth beyond the established C&L bands. However, a big challenge in its field implementation lies in the high cost and suboptimal performance of optical amplifiers, stemming from the underdeveloped state of rare-earth-doped fiber-optic amplifier technologies for these bands. Fiber-optic parametric amplifiers provide an alternative for wideband optical amplification, yet their low power efficiency limits their practical use in the field. In this paper, we study a hybrid optical amplifier that combines the excellent power efficiency of rare-earth-doped amplifiers with broadband wavelength conversion capability of parametric amplifiers. It uses wavelength converters to shift signals between the S- and L-bands, amplifying them with an L-band erbium-doped fiber amplifier, and converting them back to the S-band. We experimentally demonstrate such a hybrid S-band amplifier, characterize its performance with 16-QAM input signals, and evaluate its power efficiency and four-wave-mixing-induced crosstalk. This hybrid approach paves the way for scalable expansion of optical communication bands without waiting for advancements in rare-earth-doped amplifier technology.

Keywords: multi-band optical communication; optical amplifier; nonlinear fiber optics; parametric amplifiers; optical fiber communication



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1. Introduction

The rapid growth of streaming media platforms, cloud networking, and large language models has significantly accelerated the increase in traffic within fiber-optic networks. To meet this demand, various technologies have been explored in recent years, including spatial-division multiplexing (SDM) [1] and multi-band communication (MBC) [2]. SDM requires the development of new fiber cables, such as multi-core and multi-mode fibers, as well as complex digital signal processing (DSP) across multiple coherent receivers to counteract mode mixing in transmission links. Real-time demonstrations of SDM remain constrained to low baud rates using custom FPGA systems. Leveraging the wideband transparent window of the optical fiber, MBC offers a more straightforward approach to increasing the capacity, requiring only minor adjustments to the DSP and equalization techniques used in current systems. However, most MBC demonstrations have been limited

to the industrial and academic research labs due to the slow progress in the development of optical components for use outside of C&L bands and, especially, of suitable optical amplifiers [3,4]. Of particular interest is S-band [5], the closest band to the C&L-bands. The performance of S-band communication demonstrations is currently limited by the existing S-band amplifiers. For example, thulium-doped fiber amplifiers (TDFAs) exhibit high noise figure (NF) [6] due to the high splicing loss between the fluoride and silica fibers and require two-stage operation to optimize both the NF and the power efficiency [7]. Fiber Raman and fiber-optic parametric amplifiers (FOPAs) have poor pump efficiency, which makes all-Raman or all-FOPA communication links very costly. In addition, both of these amplifiers have significant performance issues at high gains, such as maximum gain limit due to double Rayleigh backscattering noise [8,9] in Raman amplifiers as well as maximum continuous-wave pump power limit due to the stimulated Brillouin scattering (SBS) [10] and pump relative intensity noise (RIN) transfer [11] in optical parametric amplifiers. Parametric amplification in periodically poled lithium niobate (PPLN) waveguide has been demonstrated over a 30 nm range in S-band [12], but it also suffers from the pump RIN transfer and power inefficiency due to the generation of second-harmonic pump, in addition to the fiber-waveguide coupling loss and the need for very tight temperature control to maintain the phase matching. The semiconductor optical amplifiers can operate in almost any wavelength range, but they have low saturation powers and bit-pattern-dependent gains. This restricts their operation with multiple wavelength-division-multiplexed (WDM) channels [13], although recent work [14] indicates a potential for mitigating these effects with massive WDM loading by noise-like probabilistically shaped data.

Leveraging the wideband wavelength conversion capability of a FOPA [15] and excellent pump efficiency of an erbium-doped fiber amplifier (EDFA), we proposed a hybrid S-band amplifier [16–18] with three stages, shown in Figure 1: the first stage uses a FOPA-based wavelength converter to shift the weak S-band signal to the L-band idler; the second stage uses an L-band EDFA to amplify the L-band idler; the third stage uses another FOPA wavelength converter to convert the amplified L-band idler back to the S-band signal to complete the S-band amplification. The L-band placement of the idler (e.g., as opposed to C-band) is determined by the zero-dispersion wavelength (ZDW) of the highly nonlinear fiber (HNLF) available in our lab. In the chosen regime, the two FOPA wavelength converters work in a low-gain mode, which has an acceptable pump efficiency and does not suffer from the pump RIN transfer, and the pump-power-efficient L-band EDFA provides most of the gain. The conversion efficiency (CE) of the FOPA wavelength converter is determined by the pump power, which is limited by the SBS threshold. To overcome the SBS, a phase dithering is imposed onto the pump [19]. The first-stage FOPA imprints the idler beam with double of the pump phase dithering amount, but this dithering can be undone by the third-stage FOPA, if the pump dithering at the first and third stages is synchronized by accurately controlling the relative pump-idler delays at the two stages [20]. The SBS-suppressed HNLF reported in [21–24] could potentially replace this complex and expensive synchronized pump dithering setup. The theoretical modeling and experimental measurement of the NF for the separate stages of the hybrid S-band amplifier have been described in detail in [25]. Combining different amplifier types in the same link has been frequently used in multi-band optical communications, with different amplifier types responsible for different wavelength bands, e.g., bismuth-doped fiber amplifier (BDFA) for O- and E-bands, TDFA for S-band, EDFA for C- and L-bands, and Raman amplifier for U-band [2] or BDFA for E-band and Raman amplifier for S- C-, and L-bands [26]. In contrast to that, our hybrid amplifier combines two amplifier types with complementary properties (wavelength conversion capability of the FOPA and high gain and pump efficiency of the EDFA) for amplification in one band (S-band in our case).

This approach is inspired by the example of hybrid amplification that combines the distributed property of Raman amplification with pump efficiency of a lumped EDFA to dramatically reduce the transmission span's NF without employing problem-prone high Raman gains [27]. Similarly to that, we shift the burden of providing most of the gain from the FOPA to the EDFA.

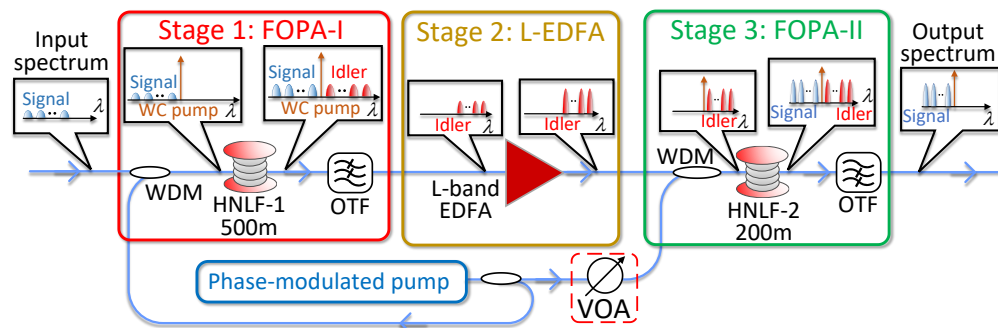


Figure 1. Concept of the hybrid S-band amplifier. EDFA: erbium-doped fiber amplifier; HNLf: highly nonlinear fiber; FOPA: fiber-optic parametric amplifier; OTF: optical tunable filter; VOA: variable optical attenuator; WC: wavelength conversion; WDM: wavelength-division-multiplexing.

In this paper, we report the detailed investigation of the system performance of the complete hybrid S-band amplifier with 16-QAM signals (briefly reported in [20]), including the experimental demonstration of its NF < 6 dB (briefly described in [28]), and study the trade-off between its power efficiency and inter-channel crosstalk induced by four-wave mixing (briefly reported in [29]). The system performance is described in Section 2 below, whereas the investigation of the power efficiency/crosstalk trade-off is presented in Section 3.

2. Performance of the Hybrid S-Band Amplifier

In this section, we present the performance of the S-band hybrid amplifier with eight WDM channels modulated by 10-Gbaud 16-QAM data, including the combined impacts of NF, nonlinearity, and imperfect cancelation of pump phase dithering in the hybrid amplifier scheme.

The experimental setup for the performance characterization is shown in Figure 2. At the input of the first stage of the hybrid amplifier, eight S-band channels on a 50 GHz ITU grid (1527.44 nm–1530.14 nm) are aligned in their polarization states by eight polarization controllers (PCs), combined by 1×8 optical coupler, and then modulated with 10-Gbaud 16-QAM data by a coherent IQ transmitter (Coherent Solutions/Quantifi Photonics, IQTX-26-EDP-ABC with a 26 GHz bandwidth, Auckland, New Zealand). The DSP at the transmitter side includes only a root-raised cosine filter with a roll-off factor of 0.7. To more accurately evaluate the nonlinear degradations of the hybrid amplifier, the modulated signal is sent through a 3 km-long dispersion compensation fiber (DCF) with -356 ps/nm dispersion to decorrelate the patterns among the adjacent channels by 1.4 symbols. The choice of long-wavelength S-band channels for this investigation is determined by the operating range of our coherent receiver.

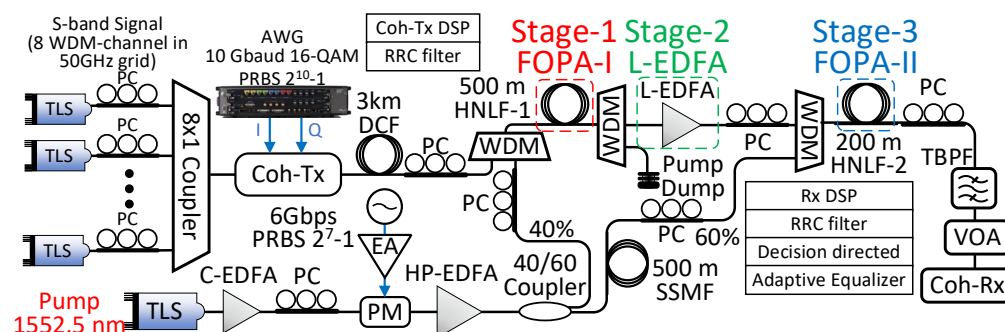


Figure 2. Experimental setup for performance characterization of the hybrid S-band amplifier. AWG: arbitrary waveform generator; C-EDFA: C-band erbium-doped fiber amplifier (EDFA); Coh-Rx: coherent receiver; Coh-Tx: coherent transmitter; DCF: dispersion compensating fiber; DSP: digital signal processing; EA: electronic amplifier; FOPA: fiber-optic parametric amplifier; HNLf: highly nonlinear fiber; L-EDFA: L-band EDFA; HP-EDFA: high-power C-band EDFA; PC: polarization controller; PM: phase modulator; PRBS: pseudorandom bit sequence; RRC: root-raised cosine; SSMF: standard single-mode fiber; VOA: variable optical attenuator; TBPF: tunable bandpass filter; TLS: tunable laser source; WDM: wavelength-division multiplexer.

The pump wavelength is 1552.5 nm, 1 nm above the ZDW of the two HNLfs used in the first- and third-stage FOPA wavelength converters (referred to as FOPA-I and FOPA-II below), to give flat conversion efficiency for the eight channels under test. At the input of FOPA-I, the WDM signals with an average power of -28 dBm per channel are combined with 40% of pump power (25.7 dBm) by a WDM coupler and sent through 500 m long HNLf (Furukawa Electric Company, Ltd.) with ZDW of 1551.5 nm, dispersion slope of 0.043 ps/nm²/km, and nonlinear constant $\gamma = 21.4$ W/km for conversion of S-band signals to L-band idlers with an average CE of 8.7 dB, yielding -20 dBm per channel for L-band idler. After FOPA-I, the L-band idler beams are filtered out by a WDM coupler and fed into an L-band EDFA with an average power of -22 dBm per channel, while the residual pump power is absorbed by a fiber-optic light trap (Thorlabs, FTAPC1) at the other output port of the WDM coupler. The amplified idlers with an average power of -5 dBm per channel after L-band EDFA are combined with 60% of pump power (27.4 dBm). The polarization states of the pump and signals (idlers) at the input of FOPA-I (FOPA-II) are aligned by polarization controllers. The amplified L-band idlers are converted back to the S-band in FOPA-II, whose HNLf has the same properties as the first HNLf but has a shorter 200 m length. The average output power of the output (amplified) S-band signal is -1 dBm per channel. For a continuous-wave (CW) pump, the CEs of the two parametric wavelength converters are limited by the SBS to -10 dB. Based on the theoretical model in [25], the CE of the first stage dominates the NF of the hybrid amplifier. To increase the CE, the pump used for the two FOPA wavelength converters is phase-modulated by a BPSK data with 6 Gbps $2^7 - 1$ pseudo-random bit sequence (PRBS) via an electro-optic phase modulator with 10 GHz bandwidth, which increases the SBS threshold of the HNLf. In FOPA-I, the double amount of pump modulation is transferred onto the L-band idlers. The fiber length between the FOPA-I and FOPA-II, including the EDFA length, is characterized, and the pump path to FOPA-II is lengthened by a 500 m long standard single-mode fiber (SSMF), so that at the FOPA-II input the delay between the L-band idler and pump bit patterns is close to a whole number of pattern periods. The fine tuning of the pattern synchronization is performed by adjusting the PRBS clock rate. Thus, the phase transfer from the phase-dithered pump is canceled after the second wavelength conversion in FOPA-II, yielding the S-band output without the phase-dithering distortion [20]. Among the output (amplified) S-band signals, we select one channel with a tunable optical bandpass filter and send it to a coherent receiver IQS70 (Coherent Solutions/Quantifi Photonics, Auckland,

New Zealand) with subsequent measurement by a real-time oscilloscope LabMaster 10-65Zi-A (LeCroy, Chestnut Ridge, NY, USA). The DSP at the receiver side includes the same root-raised cosine filter as the transmitter, a 17-tap adaptive equalizer, and a decision-directed carrier recovery.

Prior to characterizing the system performance of the complete S-band hybrid amplifier, we have measured its NF with eight continuous-wave (CW) WDM channels on a 100-GHz ITU grid (1522.56 nm–1527.99 nm), with the input power of -25 dBm per channel [28]. The NF measurement procedure and model are described in detail in [25]. For this measurement with CW signal input, Figure 3 presents the input and output signal spectra of the hybrid S-band amplifier (Figure 3a) and L-EDFA (Figure 3b), which indicate that the FOPA-II successfully compensates the phase modulation imposed by the FOPA-I, so that no net phase modulation is transferred from the phase-dithered pump to the output signal. The total gain and NF of this measurement are shown in Figure 4a, while the CEs and gains for individual stages, observed in this experiment, are presented in Figure 4b. The simulated NF in Figure 4a is calculated as a cascaded NF of a 3-stage amplifier, using the measured EDFA NF and the experimentally verified NF model for the two wavelength-converter stages [25]. The left-edge (first) channel has a lower gain of 17.1 dB and slightly higher NF of 6.7 dB, whereas the remaining seven channels have gains in a narrow 18.0 dB–19.2 dB range and NFs in a narrow 4.6 dB–5.6 dB range, as expected from our modeling [25]. The average NF among all 8 channels is 5.3 dB, which is comparable to that of an EDFA.

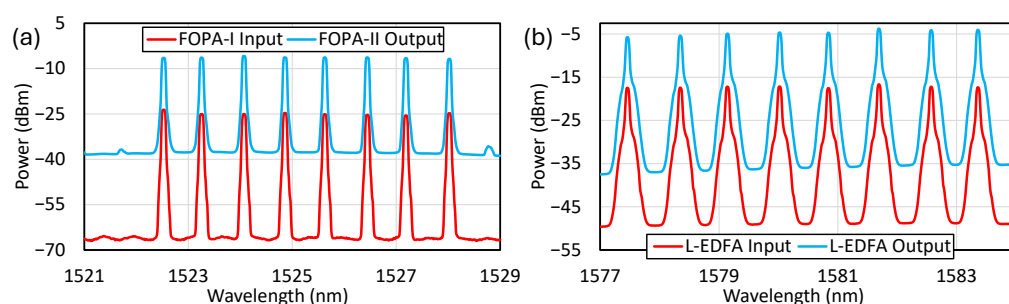


Figure 3. Optical spectra for the hybrid S-band amplifier with continuous-wave signal input, measured with 0.067 nm resolution at: (a) the input and output of the entire hybrid S-band amplifier; (b) the input and output of the L-band EDFA (stage 2).

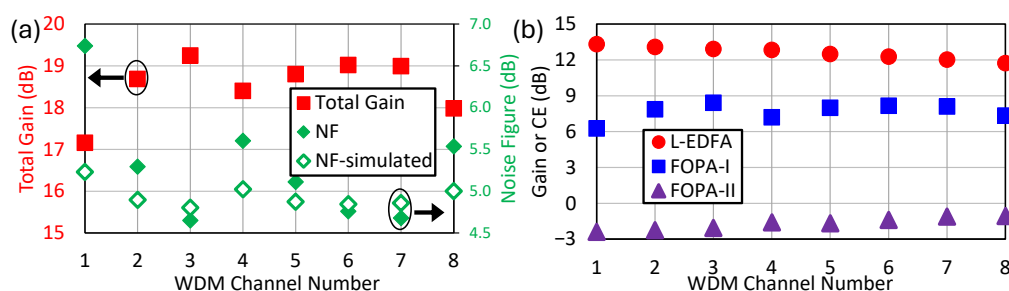


Figure 4. Noise figure (NF) measurement results with continuous-wave S-band signals [28]: (a) total gain, NF, and simulated NF using the model in [25]; (b) gain or conversion efficiency for each of the 3 individual stages of the hybrid S-band amplifier.

For our systems test, we change the input signals to eight 50 GHz spaced channels on the long-wavelength end of the S-band (1527.44 nm–1530.14 nm). This wavelength choice is determined by the tuning range of our tunable laser sources with narrow linewidths suitable for coherent communications. Figure 5 shows the input and output spectra of the hybrid amplifier as a whole and those of its middle-stage L-band EDFA. The total gain of

the S-band signal is between 25.8 dB and 27.1 dB for all eight channels, and the total gain as well as the gains or conversion efficiencies of its individual stages are summarized in Table 1 for each of the eight channels.

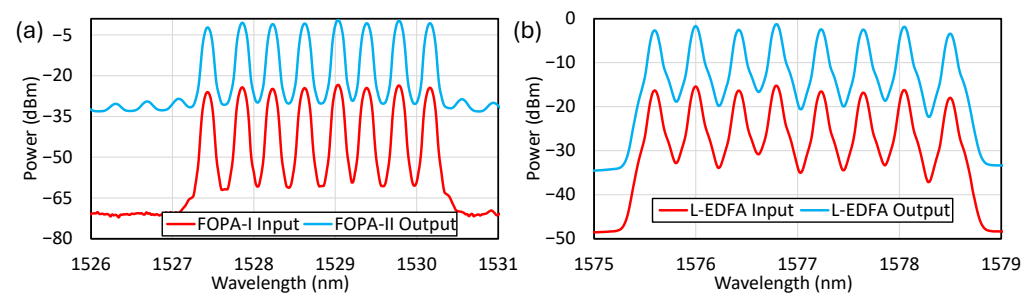


Figure 5. Optical spectra for the hybrid S-band amplifier with 16-QAM signal input, measured with 0.067 nm resolution at: (a) the input and output of the entire hybrid S-band amplifier; (b) the input and output of the L-band EDFA (stage 2).

Table 1. Summary of the conversion efficiencies (CEs) of FOPA-I and FOPA-II, gain of L-band EDFA in the middle stage, and the total gain of the hybrid amplifier for all 8 channels.

Channel Number	FOPA-I CE (dB)	L-Band EDFA Gain (dB)	FOPA-II CE (dB)	Total Gain (dB)
1	9.8	15.4	1.9	27.1
2	9.4	15.4	2.2	27.0
3	9.4	15.5	2.1	27.0
4	9.6	15.5	1.9	26.9
5	7.8	15.5	3.6	26.9
6	7.8	15.5	3.2	26.5
7	7.8	15.4	3.0	26.2
8	7.6	15.5	2.7	25.8

The overall system performance of the hybrid S-band amplifier is characterized by measuring three representative channels (#3, #5, and #8) among the eight WDM channels. Their 16-QAM constellation maps at the output of the hybrid S-band amplifier are shown in Figure 6c,f,i. The wider amplitude-dependent phase spread in the outer (especially, corner) constellation points, compared to the inner constellation points, is a signature of the nonlinear distortion induced by the self-phase modulation in FOPA-II. In the low-dispersion fiber such as the HNLF, the degradations due to the self-phase modulation, cross-phase modulation, and four-wave mixing are all determined by the nonlinear phase shifts accumulated by the signal and idler beams (primarily by the stronger L-band idler beam) in FOPA-II, which need to be kept at a minimum. Hence, to avoid significant distortion of the constellation map in our experiment, the output power of the hybrid amplifier should be kept below the approximately -1 dBm per channel level obtained under parameters shown in Table 1.

The error vector magnitudes (EVMS) and bit error ratios (BERs) versus input power to the receiver for the characterized channels are also summarized in the left and middle columns of Figure 6, respectively. The BERs of all output signals are below the soft-decision forward error correction (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.

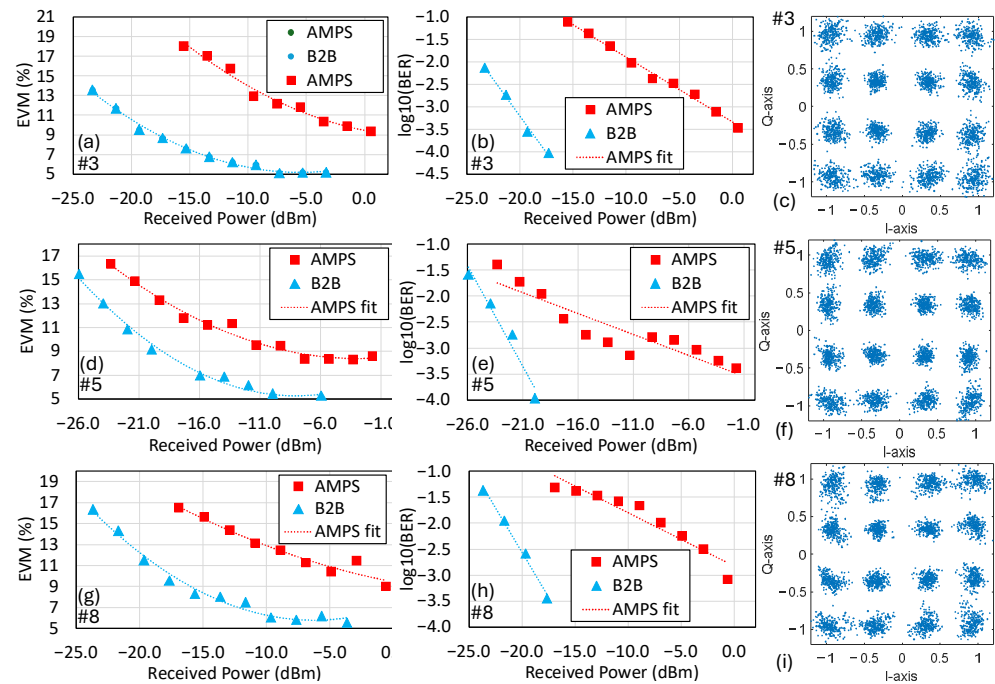


Figure 6. Error vector magnitudes (EVMs) versus received signal power for channels #3 (a), #5 (d), and #8 (g), comparing the amplified (AMPS) and back-to-back (B2B) signals. Bit-error ratios (BERs) versus received signal power for channels #3 (b), #5 (e), and #8 (h). 16-QAM constellations at the S-band hybrid amplifier output for channels #3 (c), #5 (f), and #8 (i).

To summarize this section, we have experimentally demonstrated the performance of a hybrid S-band amplifier consisting of two wavelength converters and an L-band EDFA at the middle stage with eight channels of 16-QAM-modulated S-band signal. The NF of the hybrid amplifier is found to be comparable to that of an EDFA, in line with our modeling predictions [25]. All measured channels have BERs below the soft-decision FEC threshold and power penalties roughly commensurate with the combination of the pre-amplification loss and NF of the hybrid amplifier. At -1 dBm/channel output level, 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. While our experiments have been limited to the long-wavelength portion of the S-band, this approach can be extended to the full S-band (1460 nm–1530 nm) by shifting the pump wavelength and HNLF’s ZDW and either employing both C- and L-band EDFAs at the middle stage or splitting the S-band into two sub-bands handled by separate hybrid amplifiers.

3. Power Consumption and FWM Crosstalk Analysis

To properly compare the hybrid amplifiers with other amplifiers, further investigation is needed to evaluate their performance. Pump power consumption is the most critical metric, since it limits the hybrid amplifier’s application scenarios by the cost and availability of the high-power pump sources, as well as by electric power required to drive and cool them. Our theoretical model has shown that the first-stage CE determines the overall NF and needs to be higher than 4 dB (and, preferably, around 10 dB) [25]. To achieve better power efficiency, all of the remaining gain should be obtained in the EDFA, while the third-stage CE can be, in principle, significantly less than 0 dB. The low third-stage CE, however, creates a problem of increased nonlinear degradations: to reach the target output signal power, one needs to have idlers of relatively high powers at the FOPA-II input, which generates self-phase and cross-phase modulations, as well as, and, most impor-

tantly, four-wave-mixing (FWM) crosstalk (Xtalk) among the WDM channels. In lumped ($\lesssim 1$ km long) amplifiers, the FWM Xtalk is the main nonlinear degradation [9,30,31]. Hence, the assignment of the gain and conversion efficiency to stages 2 and 3 is subject to the trade-off between the power efficiency and the FWM Xtalk: having more gain assigned to the EDFA improves power efficiency, but increases the Xtalk, while having higher CE in FOPA-II reduces the Xtalk but increases the pump power requirements. As a result, both power efficiency and Xtalk need to be investigated together.

To analyze the power consumption and FWM Xtalk of the hybrid S-band amplifier, we replace the 50 GHz spaced input WDM channels of Section 2 above with eight 100 GHz spaced CW channels, which enables easier characterization of the optical signal-to-noise ratio (OSNR) and FWM Xtalk, because the amplified spontaneous emission (ASE) floor is clearly observed in the spectrum between the 100 GHz spaced channels. We use an optical spectrum analyzer (OSA) to measure the optical spectra at the hybrid amplifier output for three signal power levels representing high (-20 dBm/ch), medium (-25 dBm/ch), and low (-30 dBm/ch) powers at the hybrid amplifier input. The criterion for estimating the power consumption is the total pump power used by the FOPA-I, FOPA-II, and middle L-band EDFA to provide a total gain of 20 dB. According to the NF analysis [25], the NF of the hybrid amplifier is primarily determined by the CE of stage 1. Hence, the FOPA-I CE is kept at +8 dB (corresponding to the FOPA-I pump power of 25 dBm), which gives a decent NF < 6 dB. By raising the pump power of the L-band EDFA and reducing the pump power of the FOPA-II (and vice versa), the 20 dB total gain of the hybrid amplifier is maintained.

In the amplified spectrum, the FWM Xtalk is calculated as the ratio of the power of the FWM tone at the place of the signal channel (when this signal channel is turned off at the input) to the power of this signal channel (when this channel is present at the input). Channel 4, which is at the center of the WDM channels, is selected to represent the worst FWM Xtalk of the hybrid amplifier. The OSNR is obtained as the ratio of the signal channel power to the ASE noise power measured within the 0.067 nm wide resolution bandwidth of the OSA. 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 the ASE noise within 0.067 nm, which accounts for both linear amplification noise and nonlinear noise-like Xtalk.

Figure 7 summarizes the OSNRs and inverse FWM crosstalks ($-Xtalk$ in dBs) for three input power levels:

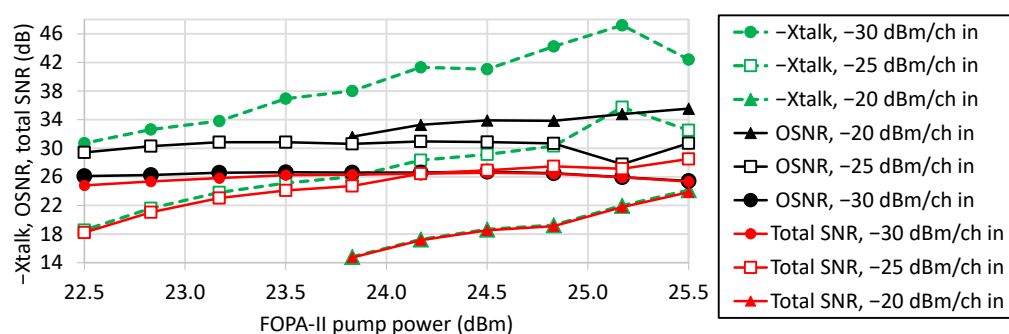


Figure 7. Inverse FWM crosstalk ($-Xtalk$, green), OSNR (black), and total SNR (red) for three input power levels (filled circles for -30 dBm/ch, empty squares for -25 dBm/ch, filled triangles for -20 dBm/ch) versus the FOPA-II pump power at a fixed 20 dB total gain.

- At low input power, the total SNR (solid red line with filled circles) coincides with the OSNR (solid black line with filled circles) for the FOPA-II pump power over 24.2 dBm. When the FOPA-II pump power is reduced to below 24.2 dBm, the pump power of L-band EDFA is increased to keep the same total gain, and the input idler power to the FOPA-II is correspondingly increased to compensate FOPA-II's low CE

owing to its weak pump power. This high input power of WDM channels at the FOPA-II input results in a total SNR deterioration by up to 1.3 dB at FOPA-II pump power of 22.5 dBm due to the generation of FWM Xtalk (dashed green line with filled circles).

- At medium input power, when the pump power in FOPA-II stage is lower than 24.2 dBm, the total SNR (solid red line with empty squares) is dominated by the FWM Xtalk (dashed green line with empty squares); for pump power between 24.2 and 24.8 dBm, the noise contributions from the OSNR (solid black line with empty squares) and FWM Xtalk are comparable; and when the pump power is above 24.8 dBm, the OSNR is dominating the performance. For low FOPA-II pump power, the third-stage CE is low, which forces the L-band amplifier to generate strong L-band idlers going into the FOPA-II, which causes high FWM Xtalk. At high FOPA-II pump powers the CE is high, and the L-band idler power going into the FOPA-II is low, which reduces the Xtalk. These observations give guidance on how to choose the FOPA-II pump power to obtain an optimal total SNR for the hybrid S-band amplifier.
- At high input power (and consequently high output power), the total SNR (solid red line with filled triangles) and $-Xtalk$ curves (dashed green line with filled triangles) coincide with each other, indicating that the total SNR of the amplified (output) S-band signal is dominated by the FWM Xtalk. Even at the highest FOPA-II pump power (corresponding to the highest CE) the total SNR is still almost 12 dB worse than the OSNR (solid black line with filled triangles). When the FOPA-II pump power is reduced to below 23.8 dBm, the L-band EDFA gain becomes saturated and cannot increase enough to achieve the total 20 dB gain target. Thus, the hybrid amplifier with FOPA-based wavelength converters cannot achieve high output powers without significant performance degradation by the FWM Xtalk. This drawback can be mitigated significantly using a platform based on the second-order nonlinearity, such as periodically poled LiNbO₃ (PPLN) waveguides [32,33], which does not produce the inter-channel FWM. However, this requires integrated PPLN photonic circuits with precise temperature tuning, which are currently custom-made and are not available commercially.

Figure 8 compares the dependences of the total SNR (red lines) and the total pump power consumption (blue lines) on the FOPA-II pump power:

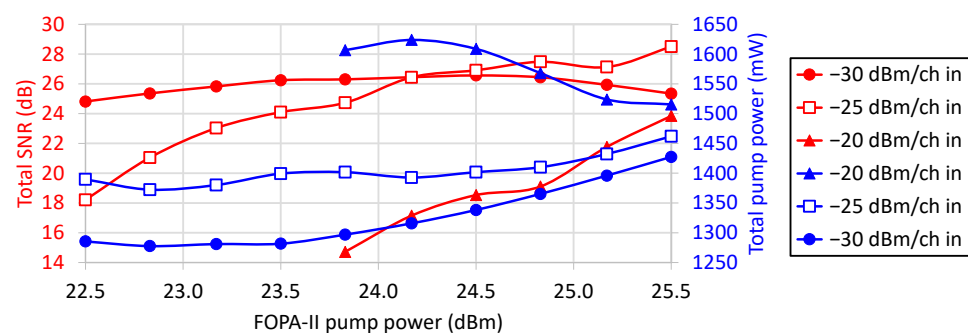


Figure 8. Total SNR (red, left scale) and total pump power (blue, right scale) for three input power levels (filled circles for -30 dBm/ch, empty squares for -25 dBm/ch, filled triangles for -20 dBm/ch) versus the FOPA-II pump power at a fixed 20 dB total gain.

- For low input power, the maximum total SNR and minimum total power consumption are achieved simultaneously when FOPA-II pump power is equal to 23.5 dBm. Since the total SNR penalty from the FWM Xtalk is very low (0.4 dB for 23.5 dBm FOPA-II pump power), the total SNR stays almost constant when the FOPA-II pump power increases. At the same time, the total pump power consumption increases, because the unsaturated (linear) L-band EDFA is more power efficient than the FOPA-

II. For the pump power below 23.5 dBm, the total pump power stays constant at ~1280 mW, because the L-band EDFA goes into saturation, where it has comparable power efficiency to FOPA-II.

- For medium input power, the total SNR monotonically increases with the FOPA-II pump power, because the higher CE of FOPA-II reduces the L-band input power in the FOPA-II, resulting in lower FWM Xtalk. The total pump power varies very little for FOPA-II powers at or below 24.5 dBm, since the L-band EDFA is working in a saturation mode with power efficiency comparable to that of the FOPA-II. Above the 24.5 dBm power point, the total SNR improvement occurs at the expense of higher total power consumption, since the L-band EDFA is working in the more power-efficient unsaturated regime, whereas any additional gain is provided by the less power-efficient FOPA-II.
- At high input power, raising the pump power into the FOPA-II stage notably increases the CE, yielding both total power savings and performance (total SNR) improvements. This is because the L-band EDFA is working in the saturation regime, losing its power efficiency advantage over the FOPA-II. Growth of the CE with FOPA-II pump power allows for lower L-band input power into the FOPA-II, resulting in lower FWM Xtalk.

To summarize this section, we have analyzed the trade-off between the FWM Xtalk and the power efficiency of the hybrid S-band amplifier by comparing the contributions of the FWM and the ASE noise to the total SNR at various pump and signal power levels. 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. Under the condition of the same 20 dB overall gain used in all our scenarios, higher input signal powers result in proportionately higher output signal powers and, consequently, generate significantly higher FWM Xtalk at the last stage. The higher input signal power also means higher OSNR. Thus, for these signals the contribution of the ASE noise to the total SNR is smaller than that of the FWM Xtalk. This situation is reversed for the low-input-power signals. The power consumption at high input signal powers can be reduced by generating higher CE in FOPA-II with the saturation-limited L-band EDFA, because the high-gain FOPA wavelength converter is more power-efficient than the saturated L-band EDFA. For medium input signal power, the signal performance monotonically increases with increasing FOPA-II pump power, whereas the power consumption stays approximately constant for FOPA-II pump power below 24.5 dBm and monotonically increases for power above that. For low input signal power, an optimal FOPA-II pump power can be found around 23.5 dBm, which achieves the highest total SNR while keeping the total power consumption at a minimum. This information is important for optimizing practical hybrid S-band amplifiers and making them suitable for possible deployment in optical transport networks.

4. Discussion and Conclusions

We have presented an experimental demonstration of an excellent performance of a hybrid S-band amplifier based on a combination of an EDFA and two fiber-optic parametric wavelength converters. Unlike other nonlinear-optics-based amplifiers, this hybrid amplifier takes advantage of the good power efficiency of the EDFA, while also benefiting from the wide bandwidth of the parametric wavelength converters. We have experimentally verified that the hybrid amplifier has a noise figure comparable to that of an EDFA, is suitable for working with coherent communications (e.g., those using 16-QAM modulation format), and is power efficient. At the same time, we have observed that its best performance and power efficiency are achieved in the scenarios where relatively low output power ($\lesssim -5$ dBm per channel) is needed. At higher output powers the nonlinear degradations in the amplifier lead to a trade-off, where the good performance can be achieved at the

expense of sacrificing some power efficiency. Such trade-offs can be potentially avoided by employing wavelength converters based on the second-order nonlinearity.

Due to its novelty, the hybrid amplifier requires some non-mainstream optical components that have not seen the mass-production yet: specialty HNLF, high-power-rated optical isolators and WDM couplers, high-power EDFA for the pump, etc. As is the case with other novel amplifiers, this may appear as a barrier to its initial deployment in real optical transmission networks, which will quickly come down when these components enter the mass production.

The demonstrated hybrid amplifier is an important enabler of extension of optical communications to the bands outside the conventional C&L bands and can be used either at the optical transmitter/receiver end or as an inline amplifier. It provides a practical solution that lowers the entry barrier to multi-band communications, while the suitable rare-earth-doped fiber amplifiers for this application are still in the development stage. Our hybrid amplifier approach has recently been applied to the U-band with the help of PPLN-based wavelength converters [32,33]. The hybrid amplifier also allows the user to leverage the mature conventional C&L-band components, such as gain equalizers, ROADMs, etc., since all the WDM equalization and network routing can be performed directly in its middle stage.

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