Broad-Band Continuous-Wave-Pumped Fiber Optical Parametric Amplifier with 49-dB Gain and Wavelength-Conversion Efficiency

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***Abstract*—A broad-band continuous-wave (CW) pumped fiber-based parametric amplifier with 49 dB of internal gain and wavelength conversion efficiency, corresponding to a black box gain/efficiency of 38 dB, is demonstrated. Bit-error-rate (BER) measurements indicate performance comparable to erbium-doped fiber amplifiers (EDFAs). These amplifiers may thus find new applications in future lightwave systems.**

***Index Terms*—Four-wave mixing, optical amplifiers, optical fibers, optical transmission, parametric amplification.**

I. Introduction

FIBER-BASED optical parametric amplifiers (OPAs) relying on four-wave mixing (FWM) in dispersion-shifted fibers (DSFs) have up to now essentially been considered not to have sufficient performance to be of interest as amplifiers in fiber communication systems, except in very particular applications. In [1], a continuous-wave (CW) pumped fiber OPA is demonstrated with a net internal signal gain (signal at fiber output/signal at fiber input) of 5 dB. However, the net black-box gain (internal signal gain minus output and input power losses) was ≈ -5 dB. In fact, no demonstration exists to date reporting net black-box gain. On the other hand, fiber OPAs in pulsed operation have reached black-box gains of $\approx$25 dB [2], [3]. These are, however, not very practical in many applications as they require synchronization of data and amplifying pulses. OPAs do, nevertheless, have many interesting properties. They include instantaneous response that can be utilized for optical limiters; they are potentially very broad-band; the center wavelength can be easily tailored by changing the fiber and pump laser; they can serve as wavelength converters with inherent gain; and they can, in principle, operate with a noise figure (NF) approaching 0 dB if implemented in a phase-sensitive mode (the quantum limited NF is 3 dB in phase-insensitive mode) [4]. In this letter we report, for the first time to the best of our knowledge, on a CW-pumped OPA with a net black-box signal gain as well as conversion efficiency. We measure a signal gain/conversion efficiency $>$1 over 56 nm centered at 1562 nm. The highest black-box gain efficiency is 38 dB. Internal net gain, without compensating for insertion and output loss, is 49 dB. In addition, the OPA is evaluated as a preamplifier, and a sensitivity is obtained that is comparable to those of erbium-doped fiber amplifiers (EDFAs). We believe our results show that fiber based OPAs may indeed be considered real candidates in future amplified lightwave systems, together with doped fiber amplifiers and Raman amplifiers.

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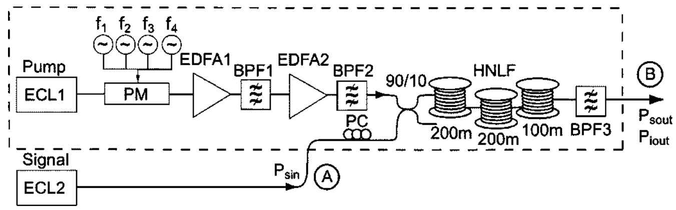

Fig. 1. OPA configuration. PC: polarization controller; BPF: optical bandpass filter; PM: phase modulator; EDFA: erbium-doped amplifier; HNLF: highly nonlinear fiber; ECL: external cavity laser.

II. Experimental Setup

The setup is shown in Fig. 1. Two external cavity lasers, ECL1 and ECL2, served as pump and signal sources, respectively. The pump wavelength, λ_p, was set at 1563 nm. The CW pump was amplified by a conventional EDFA (EDFA1), serving as a preamplifier to the second stage commercially available booster EDFA (EDFA2) with 33-dBm maximum output power. For the gain medium, three pieces of highly nonlinear fiber (HNLF) ($200 + 200 + 100$ m) were available; the zero-dispersion wavelength, λ_0, in each fiber was 1556.8, 1560.3, and 1561.2 nm, respectively, and the dispersion slope was 0.03 ps/nm^{2}km. To maximize the parametric gain, the order of the three HNLF pieces were optimized by a simplified numerical model based on the coupled wave equations in [5]. The model took into account insertion loss, varying dispersion, and splice losses (≈ -0.5 dB). Fiber attenuation, pump depletion, as well as self-phase modulation (SPM) were neglected. Maximum gain was found by arranging the fibers with an increasing λ_0. The fiber nonlinearity parameter, γ, was measured to 11.4 W^{-1}km^{-1}. In order to suppress stimulated Brillouin scattering (SBS), the pump spectrum was broadened by a phase modulator (PM) driven by four electrically combined RF-sinusoidal signals (100, 310, 910, and 2700 MHz)[6]. The frequencies were chosen to provide a flat optical pump spectra consisting of 3^4 frequency peaks separated by $\approx$100 MHz, well exceeding the Brillouin gain bandwidth measured to $\approx$50 MHz. Due to the spectral broadening, the SBS threshold

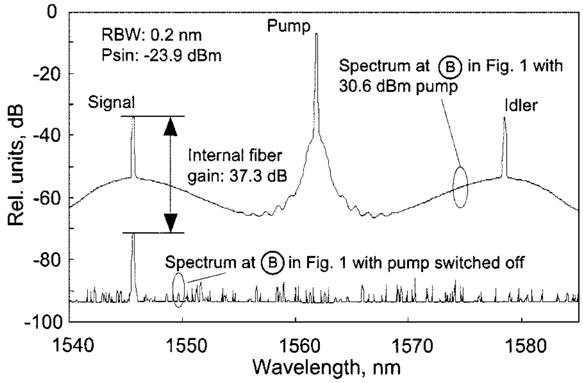

Fig. 2. Measured optical spectra at OPA output with and without 30.6-dBm pump (BPF3 removed).

was increased by more than 15 dB to above 32.2 dBm for the 500-m HNLF. The SBS suppression, i.e., the ratio between transmitted and Brillouin backscattered optical power, was thus more than 40 dB for the highest possible launched pump power into the OPA. Signal and pump were combined by a 90/10 coupler having 0.4 dB insertion loss for the pump and 9.8 dB insertion loss for the signal. The splice loss between the coupler and the HNLF was 0.8 dB. At the output of the OPA, either the idler or the parametrically amplified signal could be recovered by an optical bandpass filter (BPF3). The outcoupling loss due to BPF3 was 1.2 dB.

III. Experimental Results

In Fig. 2 the optical spectra measured by an optical spectrum analyzer at point B in Fig. 1 is shown with and without the pump turned on. The spectra shows an internal fiber gain at $\lambda_s = 1547$ nm of 37.3 dB at 31.0 dBm pump power into the HNLF, which corresponds to $37.3 - 9.8 - 1.2 = 26.3$ dB black-box gain. The input signal power, $P_{\rm sin}$ was -23.9 dBm. The measured optical signal-to-noise ratio (OSNR) was 20 dB at 0.2 nm resolution bandwidth limited by the nonideal suppression of amplified spontaneous emission (ASE) noise from EDFA2; without BPF2, the OSNR was decreased by 8 dB to 12 dB. Black-box gain (output power/input power) and wavelength conversion efficiency (converted output power/input power) were measured by comparing the signal power, $P_{\rm sin}$, at point A in Fig. 1 with the signal and idler power, $P_{\rm sout}$ and $P_{i{\rm out}}$, respectively, at point B. To maximize the pump power into the HNLF, BPF2 was removed during the gain measurements ensuring a maximum pump power of 31.8 dBm into the HNLF. Fig. 3(a) and (b) shows measured black-box gain and wavelength conversion efficiency (symbols), respectively, versus signal wavelength at different pump powers into the HNLF. Solid lines show theoretical gain and conversion efficiency according to the numerical model. To maximize the parametric gain while retaining the gain bandwidth, the pump wavelength was slightly increased to compensate for the increasing nonlinear phase shift with the increasing pump power. The pump wavelength was 1562.5 nm at a pump power of 28.8 dBm, 1563.3 nm at a pump power of 30.5 dBm, and 1563.5 nm at a pump power of 31.8 dBm. Theory and experiment showed good agreement except for the highest pump power where the pump was becoming depleted.

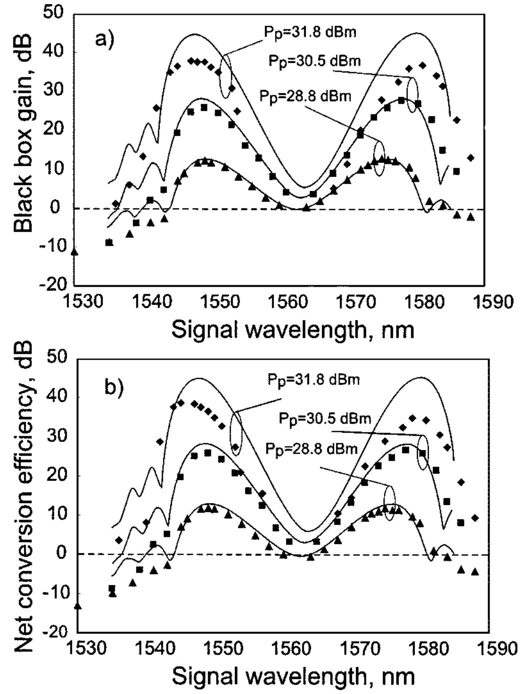

Fig. 3. Measured black-box gain, G (a) and wavelength conversion efficiency, η (b) versus signal wavelength for different CW pump power, P_p, into the HNLF. Solid lines: theory.

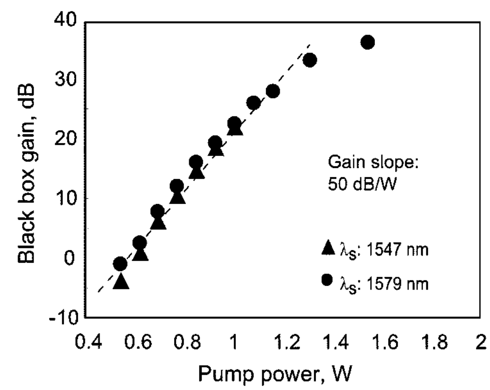

Fig. 4. Measured black-box gain versus pump power into HNLF at $\lambda_s = 1547$ nm and 1579 nm. Input signal power was -19.5 dBm.

The maximum black-box gain of 38 dB at $\lambda_s = 1547$ nm corresponds to an internal fiber gain of 49 dB. It is worth noting that the pump for a pulsed OPA will suffer from a high degree of pulse distortion due to SPM as the pump power increases. It will therefore be easier to achieve a high gain with a CW OPA. As the HNLF is short with a large λ_0 variation, the pump wavelength allocation is not very critical, say within ± 1 nm. In Fig. 3(b), we observe a wavelength-conversion efficiency >1 over 56 nm for a pump power of 31.8 dBm. Fig. 4 shows the small signal gain versus pump power into the HNLF plotted for $\lambda_s = 1547$ nm and $\lambda_s = 1579$ nm. The gain slope in the undepleted pump region is 50 dB/W. The maximum achieved output signal power was 21 dBm, limited by signal-induced SBS. The pump power to signal+idler power efficiency was 17%. Fig. 5 shows the optical spectra of pump, idler, and signal, measured by a high-resolution Fabry–Perot interferometer. Owing to the underlying FWM process, the idler spectrum broadens to approximately twice

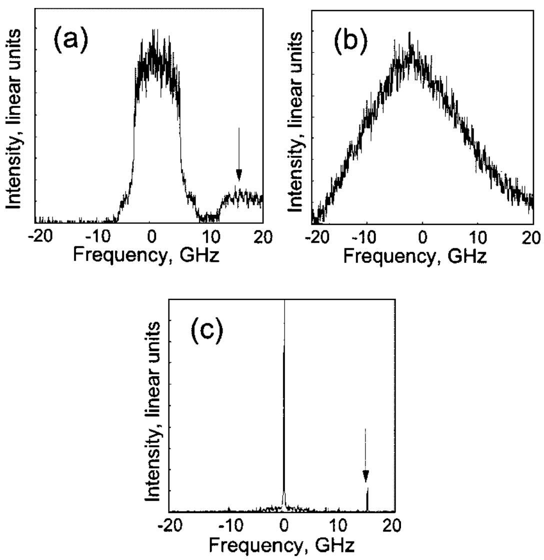

Fig. 5. Measured optical spectra (a) pump (b) idler (c) amplified signal (indicated artifacts are due to the Fabry–Perot interferometer).

the pump spectrum while the amplified signal spectrum is unaffected. This large idler broadening may be a problem for bit rates lower than or comparable to the spectral width when considering transmission of the converted wavelength signal. In [1], a method using two pumps was proposed to overcome this problem.

To confirm the feasibility of the OPA in real applications, we measured minimum required received power at BER $< 10^{-9}$ into the OPA when it was used as a preamplifier to a commercial thermal limited receiver. The signal was a 10-Gb/s $2^{15} - 1$ pseudorandom bit sequence (PRBS), nonreturn-to-zero (NRZ) pulse train at 1547 nm. To suppress ASE noise at the signal wavelength, BPF2 was reinserted after EDFA2. BPF2 limited the pump power into the HNLF to 31.0 dBm resulting in a black box gain and conversion efficiency of 26 dB at the signal wavelength. A BER curve for the wavelength converted idler was also measured by changing the signal wavelength to 1579 nm creating a wavelength converted signal at 1547 nm. Fig. 6 shows BER curves versus input average power at point A in Fig. 1. For comparison, the BER curve for the thermally limited receiver is also plotted. Even though the signal into the OPA experiences a 10 dB incoupling loss, the OPA shows a 5 dB sensitivity improvement for the signal and a 7 dB sensitivity improvement for the idler compared to the thermally limited receiver. The improved sensitivity for the idler compared to the signal wavelength is believed to originate from reduced ASE at the idler wavelength, as the idler is positioned outside the booster EDFA bandwidth. However, as can be observed from Fig. 2, there is still wavelength converted ASE noise at the idler wavelength, this results in a BER slope for both the idler and the signal comparable to conventional spontaneous noise-limited EDFAs. No PRBS word-length dependence was observed for PRBS lengths up to $2^{31} - 1$. Replacing the 10-dB coupler with a WDM coupler at the signal input branch will result in a sensitivity of -32.5 dBm and -34.5 dBm for the signal and for the converted idler, respectively. These values are comparable with EDFAs for 10-Gb/s NRZ data.

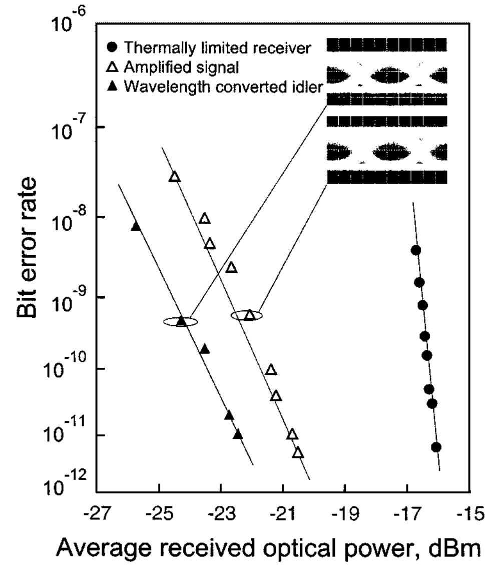

Fig. 6. Bit-error measurements for OPA with parametric amplified signal at $\lambda_s = 1547$ nm and idler wavelength converted from 1579 to 1547 nm. Black box gain and wavelength conversion efficiency were 26 dB. Inset: Eye diagrams at BER $\approx 10^{-9}$.

IV. Conclusion

We have, to our knowledge, for the first time demonstrated a broad-band, CW pumped fiber based optical parametric amplifier with performance comparable to doped fiber amplifiers and Raman amplifiers. BER measurements show sensitiveness comparable to typical EDFAs when compensating for signal incoupling loss, thus indicating a low NF. Our results indicate that fiber optical parametric amplifiers can have performance to justify their use for applications in future optical communication systems.

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References

[1] F. S. Yang, M. E. Marhic, and L. G. Kazovsky, "CW fiber optical parametric amplifier with net gain and wavelength conversion efficiency >1," *Electron. Lett.*, vol. 32, pp. 2336–2338, Dec. 1996.
[2] T. Yamamoto and M. Nakazawa, "Active optical pulse compression with a gain of 29.0 dB by using four-wave mixing in an optical fiber," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 1595–1597, Dec. 1997.
[3] P. O. Hedekvist and P. A. Andrekson, "Fiber based pulsed wavelength converter with ± 11 nm range and more than 20 dB of parametric gain," in *Proc. Eur. Conf. Optical Communication*, vol. 2, Edinburgh, Scotland, 1997, pp. 184–187.
[4] W. Imajuku, A. Takada, and Y. Yamabayashi, "Inline coherent optical amplifier with noise figure lower than 3 dB quantum limit," *Electron. Lett.*, vol. 36, pp. 63–64, Jan. 2000.
[5] J. E. Bjorkholm and R. H. Stolen, "Parametric amplification and frequency conversion in optical fibers," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 1062–1072, July 1982.
[6] S. K. Korotky, P. B. Hansen, L. Eskildsen, and J. J. Veselka, "Efficient phase modulation scheme for suppressing stimulated Brillouin scattering," in *Tech. Dig. Int. Conf. Integrated Optics and Optical Fiber Communications*, vol. 2, Hong Kong, 1995, Paper WD2-1, pp. 110–111.