Continuous-Wave Fiber Optical Parametric Amplifier With 60-dB Gain Using a Novel Two-Segment Design

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***Abstract*—We have obtained 60 dB of internal (ON–OFF) gain with a continuous-wave fiber optical parametric amplifier by using an isolator between two fiber segments to increase the pump stimulated Brillouin scattering threshold. Subdecibel penalties were measured for transmission of 10-Gb/s signals, with 35 dB of gain.**

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

I. Introduction

SINCE the first demonstration of a continuous-wave (CW) fiber optical parametric amplifier (OPA) with net internal gain [1], a CW gain of 49 dB has been demonstrated by using a 2-W pump and efficient stimulated Brillouin scattering (SBS) suppression by pump frequency dithering [2]. Demonstrating high CW gains is important for several reasons: 1) it shows that gain saturation can be reached for low signal input power, which can be used for amplitude noise reduction [3]; 2) it will facilitate obtaining CW parametric oscillation [4]; and 3) it will demonstrate that double Rayleigh scattering (DRS) does not limit OPA gain as it limits Raman amplifier gain. In order to reach higher gains, it is necessary to further suppress SBS. Doing so only by frequency dithering produced by an electrooptical phase modulator driven by radio-frequency (RF) tones becomes difficult, as it requires high RF drive powers.

In this letter, we report on a hybrid approach, wherein pump dithering is combined with another known method for increasing SBS threshold, namely the use of an isolator in the middle of the fiber [5]. The idea is that an isolator prevents backward propagation of the light reflected by SBS so that the SBS threshold of the two concatenated halves is roughly twice as high as that of an uninterrupted fiber, with the same overall length. In practice, the inevitable isolator insertion loss reduces this advantage somewhat, but it can still be significant with a low-loss isolator. In this manner, we have been able to obtain a CW gain of 60 dB, which to our knowledge is the highest gain for a CW fiber OPA reported to date.

It is important to note that the shape of the OPA gain spectrum will generally be modified compared to that of the uninterrupted fiber, because of the dispersion of the fiber pigtails inserted between the two highly nonlinear dispersion-shifted fiber (HNL-DSF) halves [6]. By inserting an extra fiber length with appropriate dispersion, one should be able to neutralize this effect.

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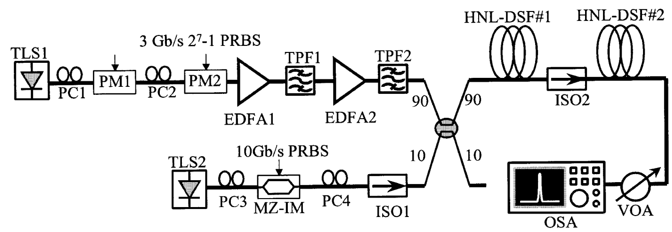


Fig. 1. OPA configuration. PC: Polarization controller. MZ-IM: Mach–Zehner intensity modulator. OSA: Optical spectrum analyzer.

We have also measured subdecibel (sub-dB) penalties for amplification of return-to-zero (RZ) and nonreturn-to-zero (NRZ) signals when this OPA is operated at a gain of 35 dB; this indicates that this SBS-suppression method is suitable for designing amplifiers for optical communication applications.

II. Experiment

The experimental configuration is shown in Fig. 1. The parametric gain medium consists of two spools of 500 m of HNL-DSF (Sumitomo Electric Industries, Ltd.) with nominal zero-dispersion wavelengths $\lambda_{01} = 1561.14$ nm and $\lambda_{02} = 1564.14$ nm, respectively. The dispersion slope is 0.03 ps/nm$^2 \cdot$ km and the fiber nonlinear coefficient γ is 17 W$^{-1} \cdot$ km^{-1}. A tunable laser source (TLS1), set at 1565.8 nm, serves as the pump source. The CW pump is phase-modulated by two phase modulators, PM1 and PM2 in cascade, to obtain a high SBS threshold. PM1 is driven by four electrically combined RF sinusoidal signals at 390, 720, 1200, and 2780 MHz, which is similar to that suggested by [7], except that we have slightly adjusted frequencies to maximize SBS threshold. PM2 is driven by a 3-Gb/s $2^7 - 1$ pseudorandom bit sequence (PRBS).

Polarization controller PC1 aligns the pump's SOP with PM1, while PC2 aligns it with PM2, which helps to reduce the insertion loss. The pump is then amplified by a C-band erbium-doped fiber amplifier (EDFA1) and filtered by a 3-nm tunable bandpass filter (TBF1). It is further amplified by EDFA2, with a maximum output power of 3 W. TBF2 is a high-power TBF with 3-nm bandwidth, which is used to reduce the ASE of EDFA2. Another tunable laser source (TLS2) is used to measure the OPA gain. Note that isolator ISO1 is used

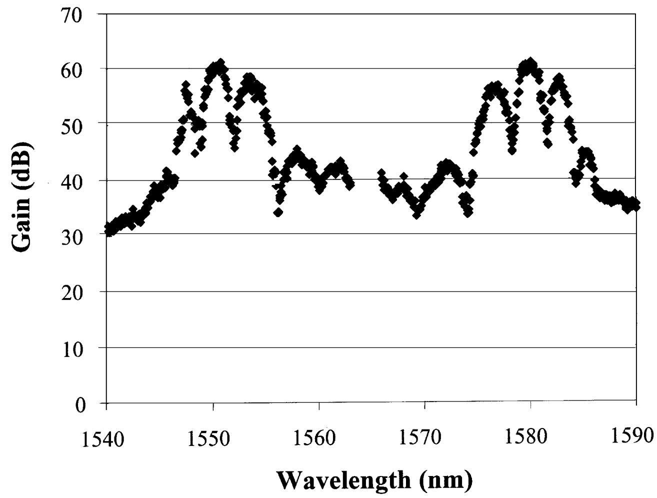
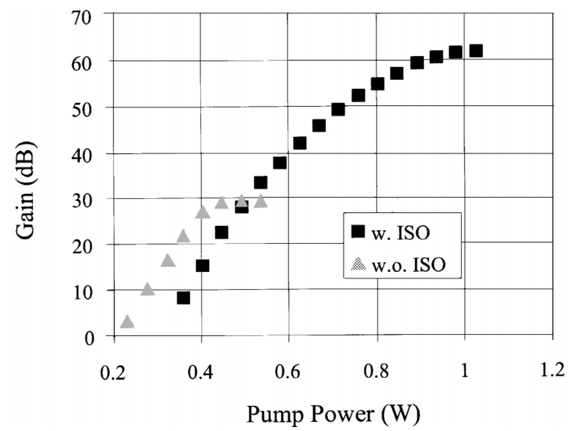
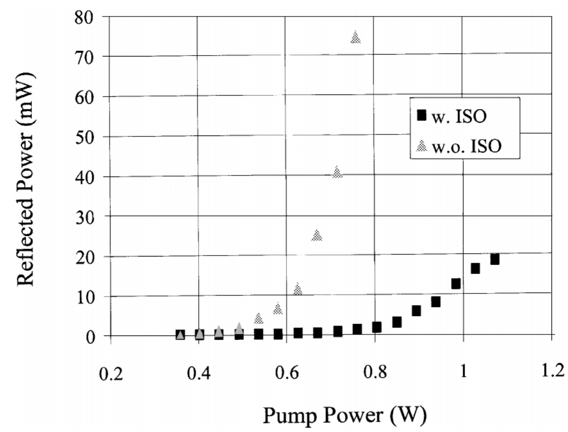


Fig. 2. OPA gain spectrum of two-segment OPA at 1.1-W pump power.



(a)



(b)

Fig. 3. (a) Gain versus pump power into HNL-DSF at $\lambda_s = 1552.5$ nm with (squares) and without (triangles) the isolator between the two spools of HNL-DSF. The gain slope is about 125 dB/W/km. (b) Reflected pump power versus incident pump power with (squares) and without (triangles) the isolator between the two spools of HNL-DSF.

to prevent any reflection (e.g., SBS) into the signal branch. The maximum OPA gain is achieved by aligning the SOPs of signal and pump by PC4. Signal and pump are combined by a 90/10 coupler, and then enter HNL-DSF#1 and #2, separated by an isolator (ISO2) with insertion loss of about 1 dB. Because of the large OPA gain, the signal input power to HNL-DSF is maintained at -40 dBm to minimize gain saturation when we measure the maximum OPA gain. However, we take advantage of the gain saturation behavior of the OPA when measuring eye diagrams and bit-error-rate (BER) curves. The signal input power is then increased to -20 dBm in order to have sufficient optical SNR to measure the BER. The output spectrum of HNL-DSF, followed by an isolator (ISO3) which prevents any reflection from the variable optical attenuator (VOA) is observed at the OSA. Eye diagrams and BER curves are measured with the digital communication analyzer and BER tester, respectively.

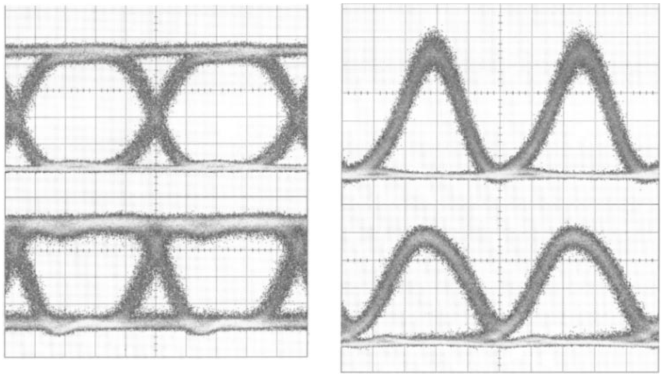
III. Results and Discussion

The experimental data for the two-segment OPA gain spectrum is shown in Fig. 2. If we carefully inspect Fig. 2, we see that there are dips at certain points in the OPA gain spectrum, as discussed in Section II. We have verified that these are due to dispersion by inserting extra patch cords with different lengths (1, 2, and 5 m); this changes the number of dips and their locations. The dips could, in principle, be eliminated by inserting a suitable length of DCF between the HNL-DSFs.

We then fixed the signal wavelength at 1552.5 nm, which corresponds to the gain peak when the pump power is 1.1 W. (Note that the gain peak varies as a function of the pump power [1].) The signal gain was measured as we reduced the pump power from 1.1 W down to 0.1 W; the result is shown as squares in Fig. 3(a). The gain slope is as high as 125 dB/W/km; this is higher than that reported in [2], because we used a higher-γ fiber. As the pump power increases, the signal output power becomes comparable to the pump power and gain saturation occurs, which reduces the signal gain at high pump power. Furthermore, the high level of ASE from EDFA2 also saturates the gain and depletes the pump [8]. Note that the OPA gain for the configuration without isolator, shown as triangles in Fig. 3(a), is clamped at about 30 dB due to SBS. However, in the linear region, it is higher than in the case with isolator due to the extra loss of the isolator.

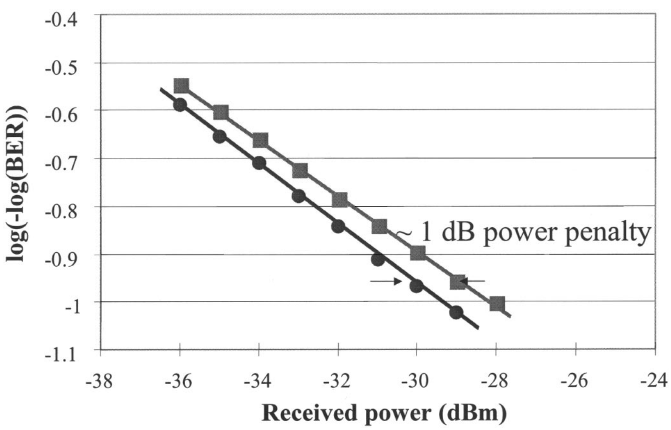
In order to verify the effective SBS suppression with this scheme, we have also measured the reflected power from the HNL-DSF, with and without the isolator between the two spools of HNL-DSF. The results are shown in Fig. 3(b) and indicate that the new scheme can increase the SBS threshold by about 3 dB, as expected.

We then investigated the feasibility of using the two-segment OPA in a communication system, by performing a transmission experiment, as shown in Fig. 1. This is important to demonstrate that fiber OPAs can operate with low penalty at relatively high gains, in contrast to Raman amplifiers, which are hampered by DRS above 25–30 dB. (This is because that the OPA has only unidirectional gain, in contrast to the bidirectional gain in Raman amplifiers.) We reduced the gain to 35 dB to have a higher OSNR than at maximum gain. We amplitude-modulated the signal by a 10-Gb/s NRZ or RZ $2^{23}-1$ PRBS and measured the power penalty due to the two-segment OPA, compared with the back-to-back configuration. Eye diagrams for the 10-Gb/s NRZ PRBS signal are shown in Fig. 4(a). The top diagram is

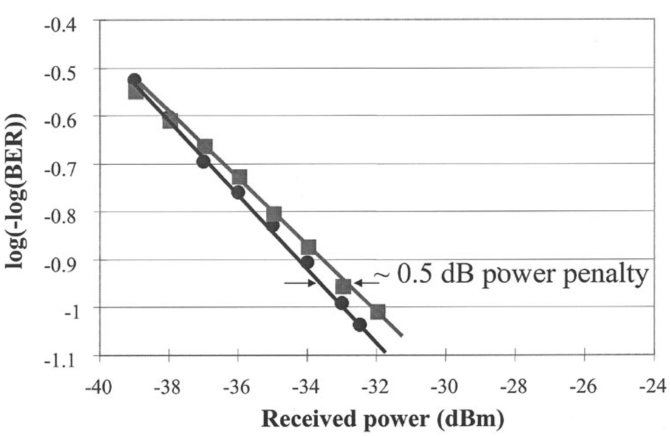


(a) (b)

Fig. 4. Eye diagram of the 10-Gb/s (a) NRZ and (b) RZ PRBS, with back-to-back configuration (top) and with the OPA (bottom).



(a)



(b)

Fig. 5. BER curve of the 10-Gb/s (a) NRZ and (b) RZ PRBS, with back-to-back configuration (circles) and with the OPA (squares).

the eye opening for the back-to-back configuration, while the bottom one is the eye with the OPA. It can be seen that the eye opening is fairly wide. The increase of the crosspoint is due to the OPA gain saturation. We take advantage of it to suppress the noise in the mark level. Similar behavior is observed when the 10-Gb/s RZ PRBS is used as signal, and the results are shown in Fig. 4(b).

In order to quantify the power penalty due to the OPA, we also measured the BER of the amplified signal. The results are shown in Fig. 5(a) and (b). Note that the power penalty is less than 1 dB when the BER is 10^{-9} for the 10-Gb/s NRZ transmission system, while it is less than 0.5 dB for the 10-Gb/s RZ system. The better sensitivity of the RZ system (-33.5 dBm compared with -30 dBm in NRZ system) is due to the receiver we used, which had a bandwidth optimized for RZ.

IV. Conclusion

We have obtained 60 dB of internal (ON–OFF) gain with a CW fiber OPA, by using an isolator between two fiber segments to increase the pump SBS threshold. The gain spectrum is different from that of an uninterrupted fiber, because of dispersion introduced by the isolator, but this could be corrected by dispersion compensation. Sub-dB penalties were measured for transmission of 10-Gb/s signals, with 35 dB of gain.

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