Noise Characterization of Raman-assisted Fiber Optical Parametric Amplifiers

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Abstract

Raman-assisted fiber optical parametric amplifiers with approaching 3-dB noise figure can be obtained by optimizing the powers of Raman and parametric pumps because of the different polarization states of the up- and down-conversion parametric spontaneous noises.

Introduction

In fiber optical parametric amplifiers (FOPAs), parametric fluorescence and spontaneous Raman scattering induced by parametric pump limit the noise performance [1,2]. In Raman-assisted fiber optical parametric amplifiers (RA-FOPAs), besides direct amplification of the signal and idler, the Raman pump also amplifies the parametric pump which in turn will amplify the signal and the idler. Due to the polarization sensitive gain of parametric amplifier, co-polarized spontaneous Raman noise induced by Raman pump will be directly coupled to forward propagating noise. As the parametric pump is also amplified by the Raman pump, its spontaneous noise will increase due to the increase in pump power. Although the over-all gain are enhanced by combing the Raman and parametric pump, the noise figure will increase as more noise source are included in the amplification process.

In this paper, we study the dominate noise source in the RA-FOPA by experiments and simulations. We found that the polarization states of up- and down-conversion parametric spontaneous noises are not aligned in highly nonlinear fiber (HNLf) based FOPA. The results indicate that approach to 3-dB noise figure can be obtained by properly choosing the powers of the Raman and parametric pumps in RA-FOPAs.

Experiment Setup

Figure 1 shows the experimental setup of the proposed RA-FOPA. A distributed feedback (DFB) laser diode served as a continuous wave (CW) parametric pump. The parametric pump was modulated by a phase modulator (PM) using pseudo-random binary sequence (PRBS) at 2.5 Gb/s in order to suppress stimulated Brillouin scattering (SBS). In addition to a 0.8 nm optical band-pass filter (BPF), we used a fiber Bragg grating (FBG) to suppress the pump noise induced by the EDFA. The signal was generated using a tunable laser source (TLS) and combined with the parametric pump using a dense wavelength de-

Figure 1: Experimental setup of a Raman-assisted fiber optical parametric amplifier.

Figure 2: FOPA parametric fluorescence spectra at different polarization states with (dot lines) and without (solid lines) a fiber polarizer placed before the spectrum analyzer. The relative differences are shown (dashed lines) in the same colors.

multiplexer (DWDM). The combined signal was subsequently launched into a 1-km long commercial dispersion-flatten HNLf via an optical circulator (CIR). The induced parametric pump had an SNR larger than 75 dB, and the wavelength is located at 1554.9 nm. The HNLf has a chromatic dispersion of 0.12 ps/nm²·km at 1555 nm, a dispersion slope of 0.01 ps/nm²·km, a nonlinear coefficient of 13.6 W⁻¹·km⁻¹, and an attenuation of 0.91 dB/km at 1550 nm. Polarization controllers (PCs) were used to optimize the parametric process. A commercial 1455-nm CW fiber Raman laser serving as the Raman pump was launched into the HNLf in the counter-propagation direction via a wavelength de-multiplexer (WDM). An isolator (ISO) is added to prevent reflection at the amplified signal and the idler wavelength. A DWDM was used to de-multiplex the parametric pump and signal/idler. The noise figure was measured using an optical spectrum analyzer (OSA) through source subtraction method [3].

Results and Discussions

To investigate the polarization state of the spontaneous noise induced by the FOPA, we turned off the Raman pump and added a polarizer before the spectral analyzer. Figure 2 shows that the measured spectra after the polarizer are different when the orientation of the PC is varied. Contrary to the observation in [2], our results indicate that the polarization states of the amplified spontaneous noise are different in the up- and down-conversion bands of FOPA and the co-polarized part of the noise does not dominate the orthogonal-polarized part of the noise. Because the FOPA gain is polarization dependent, although noise was still generated by the spontaneous emission processes, only part of them will be amplified. The noise figure thus can be approached to 3-dB quantum limit. The discussion is supported by the results in [4].

In Fig. 3, we show the measured gains and the noise figures in RA-FOPAs with different combinations of Raman pump and parametric pump powers. We note that Fig. 3(b) have better noise figure than that of Fig. 3(c), as well as a similar gain level which indicate that the powers of Raman and parametric pumps can be optimized to obtain the best noise figure. From the results, we found that RA-FOPAs with larger parametric pump will get less spontaneous noise than that with small one. This is reasonable because the spontaneous noise caused by the residual Raman pump will be reduced at the input end as the counter-propagated Raman pump gets more depletion from the strong parametric pump.

Noise in optical amplifiers can be analyzed by using quantum field operators or rate equations [1]. To study the dominate noise sources in RA-FOPAs, we found that a semi-classical approach can be used to analyze noise induced spontaneous processes. Following the model described in [5], we assumed that the Raman pump, the parametric pump, the signal, the idler and noise power densities are collinearly polarized monochromatic waves in the RA-FOPAs. In this model, we consider noises caused by parametric fluorescence, spontaneous Raman scattering induced by Raman and parametric pumps. Due to the short length of the HNLF, the coupling of noise between the co- and counter-propagating directions can also be ignored. For simplicity, parametric pump depletion caused by SBS and Rayleigh scattering are also ignored.

In Fig. 3, we also show the simulated gains and noise figures corresponding to the measurement results. In the simulations, we use the same parameters as the experiment. We also fixed the input signal and idler powers at 10^{-5} W and 10^{-11} W, respectively. The input noise power density was set at 10^{-12} W/nm. A real Raman gain profile provided by manufacturer was used.

Figure 3: Measured gains (squares) and noise figure (circles) spectra of RA-FOPAs with different combinations of Raman and parametric pumps: (a) 300 mW and 50 mW, (b) 300 mW and 100 mW, (c) 600 mW and 50 mW, and (d) 600 mW and 100 mW. Corresponding simulation results of gains (solid lines) and noise figure (dashed lines) are also shown.

Figure 3 show that the behaviors of simulated gains and noise figures match the measurement results. Pump combinations with relative large parametric pumps can get better noise figure through suppressing the spontaneous Raman emission at the input end. But, we also notice that the simulated noise figures are around 3-dB larger than the measurement ones in the amplifier gain band. The over-estimation is likely due to the assumption that the parametric pump and the spontaneous noise are co-polarized. The results also indicate that the effect of birefringence needs to be considered in the noise model of RA-FOPAs.

Conclusion

In conclusion, we found that the polarization states of up- and down-conversion parametric spontaneous noises are different in HLNLF based FOPA. The results indicate that close to 3-dB noise figure can be obtained by properly choosing the powers of Raman and parametric pumps in RA-FOPAs.

Reference

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