# Full Characterization of Noise Figure Spectrum in a Single-Pumped Fiber Parametric Amplifier

**Zhi Tong[1], Adonis Bogris[2], Magnus Karlsson[1], and Peter A. Andrekson[1]**

[1]*Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

[2]*Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, 15784 Athens, Greece*

*Email: zhi.tong@chalmers.se*

**Abstract:** For the first time, an asymmetric NF spectrum induced by both Raman induced excess noise and Raman modified pump transferred noise of a fiber parametric amplifier has been measured. Experimental results agree well with theory.



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## 1. Introduction

In theory, quantum-limited noise figure (NF) can be reached in a phase-insensitive (PI) fiber optical parametric amplifier (FOPA), however, in practice other noise sources exist, which make the quantum-limit difficult to achieve. To date, four different noise mechanisms in a practical PI-FOPA have been reported separately, which are amplified quantum noise (AQN) [1], Raman induced excess noise [2,3], pump transferred noise (PTN) [1,4,5] and residual pump noise [6], respectively. Among them, AQN is the fundamental noise mechanism, and the others can be treated as additional noise sources. AQN originates from the amplification of the vacuum quantum fluctuation and leads to the well-known 3-dB quantum limit; Raman induced excess noise comes from the delayed nonlinear response in optical fibers, which couples thermal phonons and adds noise to both Stokes and anti-Stokes waves; PTN turns pump intensity noise into signal power fluctuation instantaneously due to the ultrafast response of parametric process; Last but not least, residual pump noise is mainly due to the imperfect pump filtering, which makes a part of pump noise (mainly from the pump booster) leaking out and then being combined with the signal at the input of the amplifier. In most experimental setups, highly-nonlinear fibers (HNLF) as well as high power EDFA boosters are used to provide efficient parametric amplification. However, HNLFs usually have large Raman gain coefficients, and EDFA boosters unavoidably generate amplified spontaneous emission (ASE), as a result the additional noise contributions are not trivial in many cases, and sometimes they may dominate the noise performance.

Up to now, all the published investigations focused only on one specific additional noise in the FOPA, which may lead to inconsistent conclusions when compared to the experimental results. Moreover, it has been recognized that the true NF of FOPAs can only be measured in electrical domain, because of the narrowband nature of the PTN [2]. However, very limited electrically measured NF results have been reported, and actually no accurate NF measurements have been demonstrated over the whole parametric gain band (the measurement error in [6] is about ±2 dB). In this paper, for the first time, we take into account the four above noise contributions simultaneously to model the wavelength-dependent NF characteristics. An asymmetric NF spectrum is observed both theoretically and experimentally, which is due not only to Raman induced excess noise but also to the asymmetric PTN caused by Raman gain. Very good agreement is obtained between theory and electrical measurement, which proves that the noise performance in a PI-FOPA is determined by the combined noise contributions.

## 2. Theory

The NF of a PI-FOPA considering all four noise sources can be expressed as

$$NF_{total} = NF_{AQN} + \Delta NF_{Raman} + \Delta NF_{PTN} + \Delta NF_{Res}. \quad (1)$$

In Eq.1, $NF_{AQN} = 2 - 1/G_s$, where $G_s$ is the signal gain [3]. We use the analytical equations in [2] to calculate $NF_{AQN} + \Delta NF_{Raman}$ by assuming a linear and co-polarized parametric amplification. The imaginary part of the Raman susceptibility is obtained from direct measurement, while the real part is derived through the Kramers-Krönig relation. For the pump transferred noise, we use the 1st order approximation to model it, as shown in [4]. In Fig. 1(a), we calculate the gain and the NF spectra with or without the Raman effect (no PTN), while in Fig. 1(b) we compare the NF spectra with or without the Raman gain (no Raman induced excess noise) at different input signal level. The results clearly show that both Raman induced excess noise and Raman gain modified PTN will lead to an

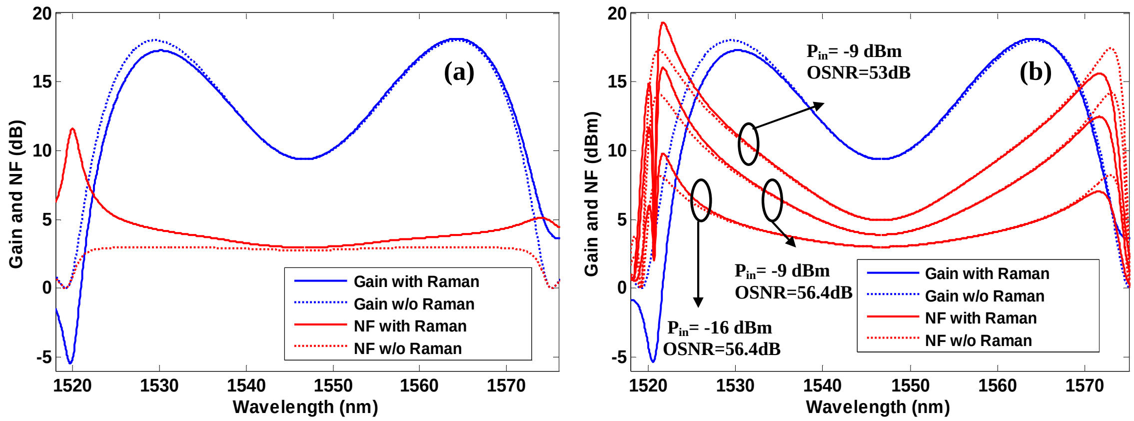


Fig. 1 a) Calculated signal gain and NF spectra with or without Raman effect (AQN + Raman induced excess noise), and b) the gain and NF spectra with or without Raman gain (AQN + PTN). Calculation parameters are the same as those used in experiments.

asymmetric NF spectrum [3], where higher NF can be seen at the anti-Stokes band. For pump residual noise, $\Delta NF_{\mathrm{Res}}$ , The following equation is used to calculate the corresponding additional NF:

$$\Delta NF_{\mathrm{Res}} = [2(G_s - 1)(S_{ASE\_Signal} + S_{ASE\_Idler}) \cdot F(\lambda)] / G_s h\nu_s \, , \tag{2}$$

where $S_{ASE\_Signal}$ and $S_{ASE\_Idler}$ represent the ASE spectral density (at the output of the EDFA booster) at signal and idler wavelengths, respectively, which can be measured by using an optical spectrum analyzer, $v_s$ is the signal frequency, and $F(\lambda)$ is the transmission response of the pump filter.

## 3. Experimental results and discussion

In Fig.2 the experimental setup is demonstrated. A 20 mW output DFB laser (1546.7 nm) was used as the pump laser, which was phase-modulated by four tones (100, 300, 900 and 2700MHz) to suppress stimulated Brillouin scattering. After a high power EDFA booster, the amplified pump was filtered and combined with signal by a 10 dB coupler. A 250 m HNLF (parameters are $\lambda_0$=1542nm, $\gamma$=11.7 $W^{-1}km^{-1}$ and $S_0$=0.019 $ps/nm^2 \cdot km$) were used as gain

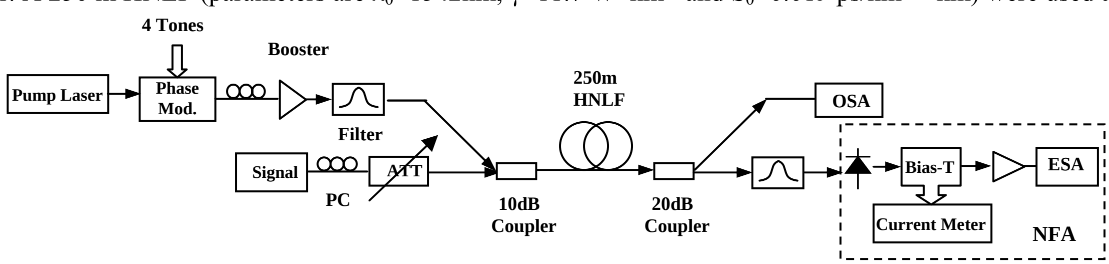


Fig.2 Measurement setup. NFA: Noise figure analyzer; ESA: Electrical spectrum analyzer; OSA: Optical spectrum analyzer; PC: Polarization controller; ATT: Variable attenuator.

medium. Finally the amplified signal was filtered and detected by the NF analyzer, as shown in Fig. 2. The detected signal and noise components were separated by a bias-T, and then measured by a current meter and electrical spectrum analyzer, respectively. It should be noted that a high-efficiency photodetector as well as a low-noise RF-amplifier is important for good accuracy. After carrying out calibration for shot noise and subtracting laser RIN noise, accurate NF and ESNR can be measured in electrical domain even for low gain. We choose 874.6 MHz as the central frequency to measure noise level, with 2 MHz resolution bandwidth and 3 Hz video bandwidth. In most cases, the NF measurement error is within ± 0.35 dB.

Firstly, the measured and calculated gain and NF spectra with only one pump filter (3dB bandwidth of 2nm) are shown in Fig. 3(a), while the output EDFA ASE spectrum is shown in Fig. 3(b). Only two fitting parameters were used in the calculation, i.e. pump power $P_P$ = 0.9 W and the $4^{th}$-order dispersion $\beta_4$ = $2\times10^{-55}$ $s^4/m$. Other parameters are directly obtained from the measured data. Very good agreement between calculated and measured gain/NF spectra can be observed, and obvious NF increase can be found close to the pump wavelength due to the pump residual ASE. The gain profile remains the same at the two different signal input levels, which confirms the linear operation regime. In Fig.4, we show measured and calculated the NF spectrum with two cascaded filters ($1^{st}$ filter: 2nm bandwidth, and $2^{nd}$ filter: 0.2nm bandwidth) to effectively suppress the pump noise, and also very good agreement is obtained at 56.2dB and 52.3dB pump OSNR, which confirms our theoretical model further. The pump

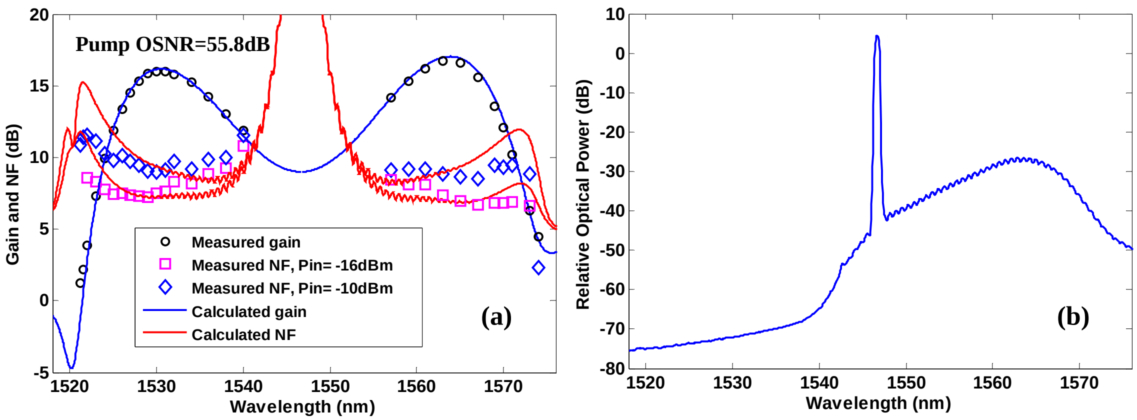


Fig.3 a) Comparison of the calculated and measured signal gain and NF spectra with only one pump filter (2nm 3-dB bandwidth), and 0.95 W pump launched power is used in calculation, and b) the ASE output spectrum of the booster.

OSNR is altered by changing the input laser power to the booster, while keeping the output power constant. A significant NF increase within ±10 nm range around pump wavelength can be observed in Fig. 3(a), which is clearly due to the pump residual ASE noise. This result indicates that pump filters with high selectivity must be used to minimize such impacts. In addition, asymmetric NF spectra have been shown in Fig.4 as expected. The deviation between the calculated and measured NF spectra may be attributed to 1) polarization misalignment between signal and pump waves, due to the polarization mode dispersion and the nonlinear polarization rotation and 2) zero-dispersion-wavelength fluctuations induced gain spectrum distortion, which can average the sharp gain decrease and thus reduce the NF at the gain edge to some degree.

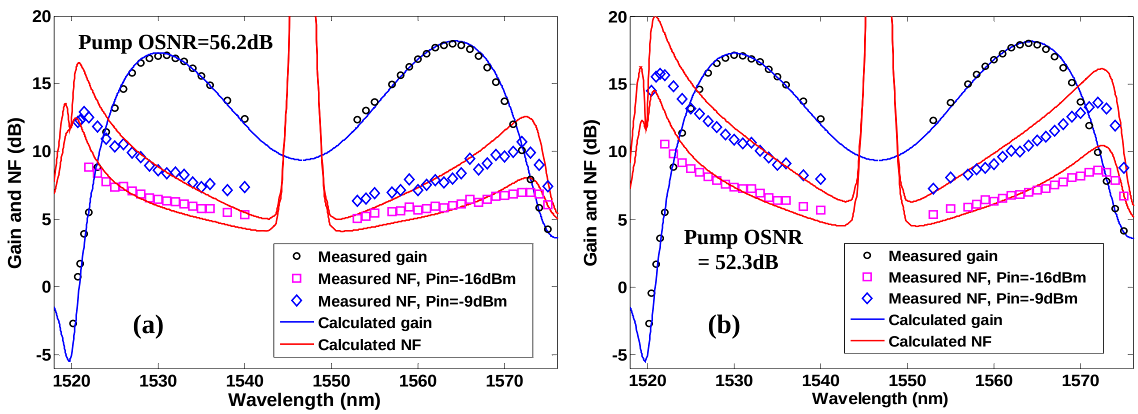


Fig. 4 Comparison of the calculated and the measured signal gain and NF spectra with two cascaded pump filters (1nm 3-dB bandwidth), with a) 56.2 dB and b) 52.3dB launched pump OSNR.

## 4. Conclusion

The full wavelength-dependent NF characteristics of a single-pumped FOPA have been studied both theoretically and experimentally by considering four noise sources in combination. Measured results agree with theory very well. Both Raman induced excess noise and Raman gain induced tilted PTN contribute to an asymmetric NF spectrum.

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