Noise Figure Measurements in Phase-Insensitive and Phase-Sensitive Fiber Parametric Amplifier Cascade

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Abstract: By cascading two non-degenerate inline fiber-optic parametric amplifiers, we observe NF ~2dB (beating phase-insensitive quantum limit) at 16-dB gain for the second (phase-sensitive) stage after subtracting the excess noise from the first (phase-insensitive) stage.

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1. Introduction

One of the unique benefits of a fiber optical parametric amplifier (FOPA) is the idler generation, which is a conjugated copy of the signal. By taking advantage of the idler wave, one can possibly achieve better noise performance than conventional EDFAs in a fiber communication system. The simplest way is to use a phase-insensitive (PI) FOPA to amplify the signal in the first span, and then maintain the generated idler in successive spans. The pump power can be distributed along the transmission fiber or blocked before each fiber span and then locally re-amplified. Better than PI quantum-limited NF of the whole system can be expected [1] since the following stages work as phase-sensitive amplifiers (PSAs). Other than noiseless amplification, some unique advantages can be derived from these non-degenerate PSAs, such as exponential gain and WDM compatibility etc, compared with degenerate cases [2]. Another benefit of this configuration is that automatically phase-locked pump, signal and idler can be prepared through the phase-insensitive amplifier (PIA), thus complicated phase-locking loops are not required during the transmission [3]. Tang *et al* have evaluated such a cascaded system with two FOPAs and a 60km SMF in between through bit-error-rate measurement [4], which shows better BER than using a PI-FOPA in the second stage. However, the comparison of BERs from phase-sensitive (PS-) and PI-FOPAs is not sufficient to demonstrate surpassing the PI quantum limit, since the noise performance of the phase-insensitive FOPA is expected to be worse than that of the ideal PIA due to the Raman induced excess noise and pump transferred noise [5].

The most straightforward way to evaluate the noise performance of a PS-FOPA is to measure its noise figure (NF). To date, less than 1dB NF has been reported for non-degenerate PS-FOPAs by measuring signal and idler separately [6,7]. However, according to [2,8], the ideal NF should be -3dB when considering signal or idler alone, which corresponds to a 0dB "real" NF of a combined signal-idler mode. It means that the previous measurements are still above the PIA limit. A NF below the PIA quantum limit can be claimed only when negative NF for both signal and idler are measured. In this paper, we measure the NF of a parametric PIA + PSA cascade with 10dB mid-stage loss in the electrical domain to emulate the inline amplification. For the first time, the non-degenerate PSA with NF better than an ideal PIA is clearly verified. Negative signal and idler NFs for the PSA stage have been obtained after subtracting the PIA excess noise, and a <2dB 'real' NF (>1dB lower than the PIA quantum limit) is estimated at >16dB gain for the second PSA stage, which is the lowest NF ever measured in a non-degenerate PSA.

2. Noise characteristics of a PIA + Attenuation + PSA cascade

The basic scheme of the cascaded FOPAs is shown in the inset (a) of Fig.1, where the transmission fiber can be viewed as an inter-stage loss. The semi-classical noise expression of a two-FOPA cascade has been obtained by assuming large photon numbers and signal beat noise dominating through quantum theory:

$$S_{PIA+ATT+PSA} = 4R^2 G_{12} P_{in} \cdot \frac{h\nu}{2}[(2G_{12} + 2G_{PIA,2}(1-T) - 1)], \quad (1)$$

where $S_{PIA+ATT+PSA}$ is the power spectral density of the total noise output at the signal wavelength, R is the ideal photo-detector responsivity, P_{in} is the input signal power, and $h\nu/2$ is the power spectral density of the vacuum fluctuation. Subscripts 1 and 2 represent the first and the second FOPA, respectively. G_{PIA} denotes the PI gain, while G_{12} is the total gain of the cascade. We have $G_{12}=G_{PIA,1}G_{PSA,2}(\theta)T$, where $G_{PSA,2}$ is the PS gain in the second stage, which depends on the relative phase, θ, between pump, signal and idler, T is the mid-stage attenuation (ATT) which is assumed identical for both signal and idler. When θ is optimized, we have $G_{PSA\text{-}max} \approx 4G_{PIA}$. The meaning of Eq.1

is that, the correlated noise (generated from the first parametric PIA) and the uncorrelated noise (induced by the mid-stage ATT) will experience different gain in the following PS- FOPA. For the PIA + ATT cascade, we have

$$S_{PIA+ATT} = 4R^2 G_{PIA,1} T P_{in} \cdot \frac{h\nu}{2}[(2G_{PIA,1}-1)T+(1-T)] \cdot \quad (2)$$

Considering the transparent transmission i.e. $G_{PIA,1} = 1/T$, and the maximum PS gain, we have the NF expressions as

$$NF_{PIA+ATT+PSA} = 2 + (2G_{PIA,2} - 2TG_{PIA,2} - 1)/G_{PSA-\max,2}, \text{ and } NF_{PIA+ATT} = 3 - 2/G_{PIA,1}. \quad (3)$$

In the high gain regime, we have $NF_{PIA+ATT+PSA} \approx$ 4dB and $NF_{PIA+ATT} \approx$ 4.8dB. This interesting result clearly shows that the PS-FOPA actually improves the total NF at the signal wave, which confirms the negative NF prediction. As is well known, the quantum limit of cascaded PIAs (e.g. EDFA) with 0dB net span gain can be written as $NF_{PIA+ATT+PIA} = NF_{PIA+ATT} + NF_{PIA,2} - 1 \approx$ 6dB, which is 2dB higher than the cascaded PIA+ATT+PSA case. The above analysis is only valid in the positive gain regime, otherwise the noise-noise beat term will be non-negligible.

3. Experimental results and discussions

Fig.1 shows the experimental setup. A 60mW low-noise DFB laser (1554.4nm) was used as the pump laser, which was phase-modulated to suppress stimulated Brillouin scattering. After an 8.5W EDFA booster followed by two cascaded 2nm filters, the amplified pump was combined with signal by a 10dB coupler. 50m and 500m highly nonlinear fibres (HNLF, parameters are λ_0=1552nm, γ=11.8 $W^{-1}km^{-1}$ and S_0=0.02 ps/nm^2 ·km) were used as the PIA and PSA, respectively. In between the two stages, another SMF-based 10dB coupler (SMF length = 7m) was inserted as the mid-stage attenuator as well as the signal/idler/noise monitor. In linear regime, this 10dB coupler can be viewed as a 50km SMF with dispersion compensation. We connected the 10% port to the input of the PSA. A 20dB coupler was spliced after the PSA to monitor the output spectrum, and two cascaded filters were used to effectively filter out the residual pump and the amplified noise. Finally the amplified signal and idler were detected by the NF analyzer. The detected signal and noise components were separated by a bias-T, and then measured by a current meter and electrical spectrum analyzer, respectively. After carrying out calibration for shot noise and subtracting laser RIN noise, accurate NF can be measured. We choose 894.7 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 ±0.4 dB. The output spectrum of the PSA is shown in the inset (b), which clearly shows the PSA gain changes with the relative phase. Compared with our previous work [5], better pump OSNR (about 60dB), longer PSA HNLF and longer SMF length (to have the peak PSA gain closer to the pump wavelength to reduce both Raman and pump transferred noise) are adopted here, thus better NF can be expected at larger PSA gain.

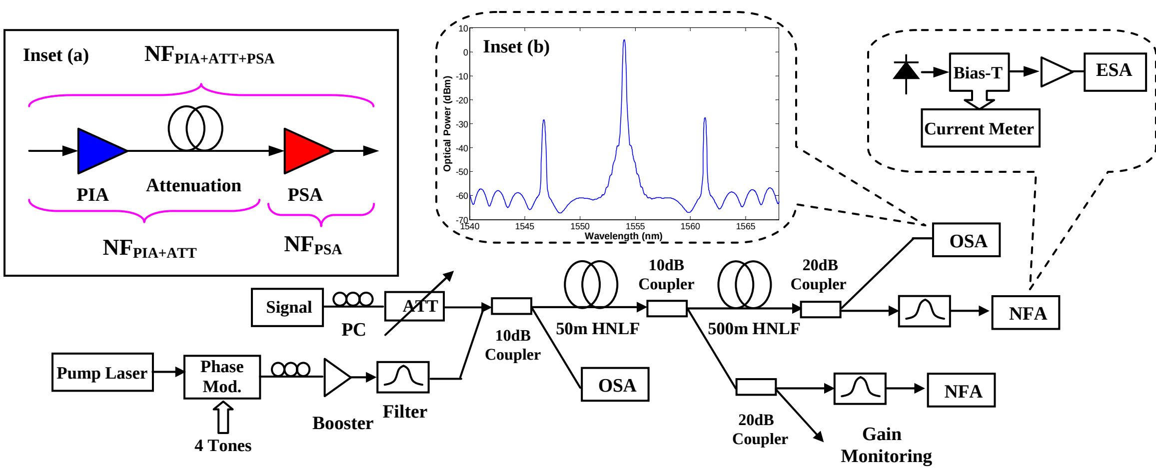

Fig.1 Measurement setup. NFA: Noise figure analyzer; ESA: Electrical spectrum analyzer; OSA: Optical spectrum analyzer; PC: Polarization controller; ATT: Variable attenuator. Inset (a) shows the principle scheme, and inset (b) shows the output optical spectrum.

In our setup, 10dB average PIA gain was achieved in the first stage, which leads to well equalized signal and idler powers input to the PSA. Average input signal power is -19.4dBm to reduce the pump noise transfer. Fig.2 shows the measured PIA, PSA gain spectra as well as the NF spectra of the PIA+ATT cascade and the total cascade. We can see that at the peak PSA gain, $NF_{PIA+ATT+PSA}$ is very close or even slightly lower than $NF_{PIA+ATT}$, indicating no degradation due to the presence of the PSA stage. The total NF degradation close to the pump is due to the strong pump residual ASE noise induced measurement errors. For comparison, we also measured the NF of an

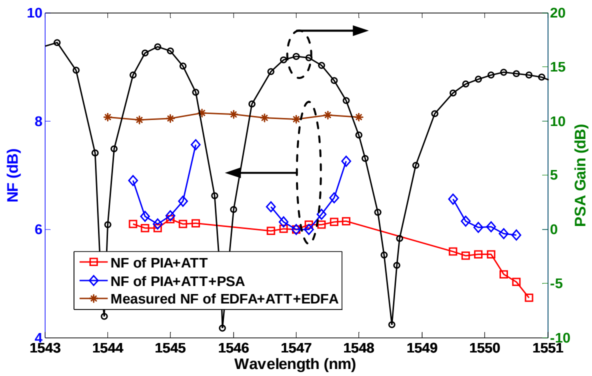

Fig.2 Measured PSA gain and NF spectra of different cascaded cases.

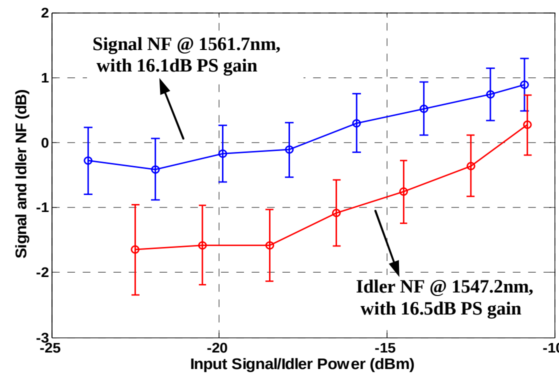

Fig.3 Measured signal and idler NF at different input power.

EDFA+ATT+EDFA cascade (total NF is about 8dB). The NF as well as the net gain of the EDFA+ATT part was almost equal to that of the PIA+ATT case (with 6dB NF and 0dB net gain, respectively), while the second EDFA has a 4.5dB NF. The results show that under the above condition the cascaded FOPA has a 2dB NF advantage.

Furthermore, we measured the PSA NF by using the RIN subtraction method to subtract the excess noise generated from the first PIA [5]. While RIN subtraction method is good for PIAs, it is not very accurate for PSAs. Namely, the RIN subtraction will overestimate the signal NF while underestimate the idler, since they will experience different gain compared to that of the excess noise. If the signal and idler powers are exactly the same at the PSA input, then the ideal PSA NF measured by RIN subtraction is NF=0.5+0.5T (-2.6dB when T=0.1) for both signal and idler, according to Eq.1 and 2. If the signal and idler powers are different at the PSA input, still the same PSA NF expression is obtained by taking the average of the signal and idler NFs. Thus, a -3dB NF can be measured when T=0 (shot-noise limit input). For the best results (signal NF at 1561.7nm: -0.4dB, idler NF at 1547.2nm: -1.7dB) as measured in Fig.4 at about -22dBm input, the averaged NF is -1 dB (i.e. 1.6 dB above the –2.6-dB NF expected for the ideal PSA in the RIN subtraction method) which means that the actual "real" PSA NF is approximately 1.4dB below the 3dB PIA quantum limit. The 1.6dB NF increase is mainly due to the Raman and pump transferred noise (the latter can be clearly seen from the NF increase with the input signal power, as shown in Fig.3). In Fig.4, the gain and the NF spectra of both signal (Stokes band) and idler waves were measured, and negative NF for both signal and idler can be observed at larger than 16dB PSA gain, with less than ±0.55dB error.

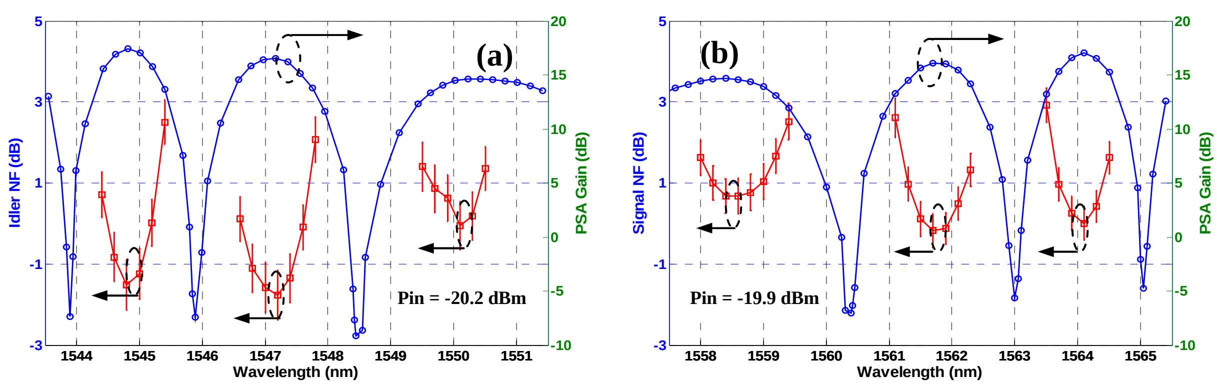

Fig.4 Measured gain and NF spectra of a) idler and b) signal waves. The NF increase close to the pump is due to the residual ASE noise.

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