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Effect of Pump Dithering at Each Stage of Cascaded Fiber Optical Parametric Amplifier

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Abstract

Cascaded fiber optical parametric amplifier (FOPA) can enhance gain and bandwidth. The gain and bandwidth can be further enhanced by dithering the FOPA pump. However, to our knowledge, the effects of a pump dithering at every stage of cascaded FOPA have not been discussed. The study of performance at every stage of cascaded FOPA is quite interesting and beneficial in designing the system. Here, we analyzed, using OptiSystem software, each stage of a cascaded FOPA, when there was a pump dithering and not. The results showed that the pump dithering enhanced the gain and broaden the bandwidth at every stage. The gain and bandwidth obtained with the pump dithering were 27 dB and 20 nm, respectively. On the other hand, when there was no pump dithering, the gain and bandwidth were 9 dB and 12 nm, respectively.

Keywords*: fiber optical parametric amplifier; pump dithering; four-wave mixing*

1. Introduction

Fiber optical parametric amplifiers (FOPAs) have obtained many research interest as the amplification bandwidth can be tuned to S-C-L band and surpass the bandwidth of erbium-doped fiber amplifiers or Raman amplifiers [1]. Several researches were conducted on FOPAs to obtain high gain or broad bandwidth. One of the methods to enhance the gain or the bandwidth is by using cascaded FOPA [2-4].

Cascaded FOPA is FOPA with two or more active media, commonly, highly nonlinear fiber (HNLF). Devices such as isolators and fiber-Bragg gratings can be inserted in between the HNLFs to intensify the gain or the bandwidth of FOPA [5,6]. Besides that, dispersion compensating single mode fiber has been demonstrated to be in between the HNLFs which can act as a phase shifter [7]. The gain and bandwidth of cascaded FOPA can further be enhanced by dithering the pump of the FOPA [8].

In reference [8], the output at each stage of the cascaded FOPA was not discussed in details. Here, we extend the study of cascaded FOPA with and without pump dithering, by observing the signal power at each stage of the cascaded FOPA. The result at each stage is crucial to ensure that the cascaded FOPA is working smoothly.

In this work, the cascaded FOPA is simulated by using OptiSystem software. The cascaded FOPA has four stages of HNLF with different dispersion characteristics and lengths, as discussed in [8]. The gain and bandwidth obtained in the simulation are compared with the experimental results in [8] to see the validity of the simulation. The effects of pump dithering are compared with the cascaded FOPAs without the pump dithering.

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2. Stimulated Brillouin Scathering (SBS) and Pump Dithering

FOPA adopts the nonlinear effect of four-wave mixing, usually hindered by SBS that generate backward wave in HNLF, which limits the input power of FOPA. Accordingly, the SBS also implies a strict limit to the pump power that can be delivered to the HNLF. The SBS occurs when the power in optical fiber is more than SBS threshold. After the SBS power threshold, almost any additional power increase will be backscattered by SBS. The SBS power threshold is defined as:

$$P_{th} \approx \frac{21kA_{eff}}{g_o L_{eff}} \left[\frac{\Delta v_B \Delta v_P}{\Delta v_B} \right], \tag{1}$$

where k is the wave polarization state, A_{eff} is the effective area of the optical fiber, L_{eff} is effective interaction length, g_o is the Brillouin gain parameter, Δv_B is Brillouin gain bandwidth, and Δv_p is incident pump linewidth.

From equation (1), it can be seen that the SBS power threshold depends on the pump linewidth. The SBS threshold can be increased by broadening the pump linewidth, or called as pump dithering. Pump dithering is a common method used to overcome the SBS in FOPA. By broadening the pump linewidth, the coherent buildup of the generally narrow SBS is reduced [9]. Pump dithering usually be done by phase modulated pump to more than the SBS bandwidth, which is typically tens of MHz. The electrical signal driving the phase modulator is typically a few radio-frequency (RF) tones. Besides RF, a pseudo-random bit sequence or amplified spontaneous emission can also be used. This method can increase the SBS power threshold many times.

In addition, isolator can be used to reduce the back reflection light. Our setup combined both methods of SBS suppression: pump dithering and isolator.

3. Structure of Cascaded FOPA

The simulation setup can be referred from [8]. Figure 1 illustrates the structure of the cascaded FOPA with the pump dithering.

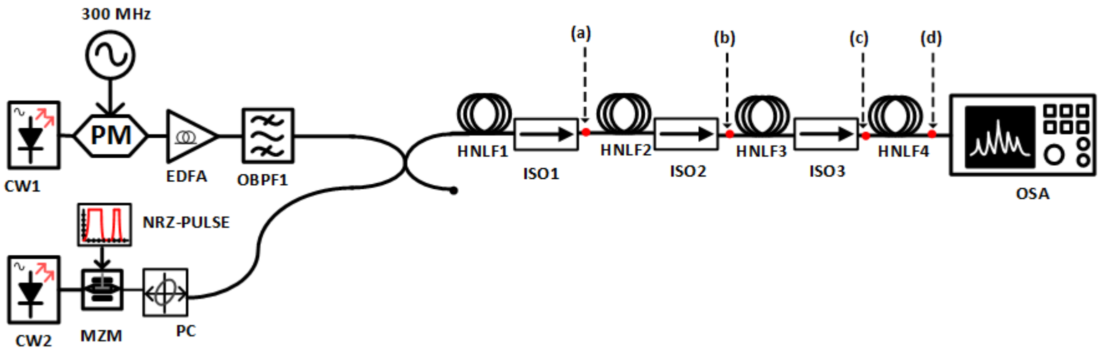

Figure 1. Simulation setup of cascaded FOPA with 300MHz RF tone

The pump light at 1554.1 nm is amplified by an erbium-doped fiber amplifier (EDFA). Then, it is filtered and coupled to a signal with a Wavelength Division Multiplexer (WDM) coupler. The signal is modulated by 10 Gbit/s data in on-off keying (OOK) format by using a Mach-Zender modulator. For the setup with pump dithering, RF tones are phase modulated in the pump at 300 MHz to enhance the linewidth broadening and this has resulted in an extremely efficient SBS suppression. Subsequently, the signal is selected by a set of optical filter at the output. Table 1 lists the parameters of four HNLFs used at every stage of the FOPA.

Table 1. The parameters of four HNLF

Parameter	HNLF1	HNLF2	HNLF3	HNLF4
Length (m)	114	143	182	253
Fiber attenuation (dB/km)	0.86	0.86	0.77	0.77
Zero dispersion wavelength (nm)	1541.6	1542.4	1535.8	1532.0
Nonlinear coefficient ($W^{-1} km^{-1}$)	11.7	11.7	11.7	11.7
Effective area (μm^2)	10.5	10.5	10.5	10.5

4. Result and Analysis

For the result, first, we compare the gain and bandwidth obtained from our simulation with the gain and bandwidth obtained experimentally in [8] to validate our simulation. Figure 2 shows the FOPA gain, with and without pump dithering, obtained from the experimental and the simulation works. The black and gray curves with dots are the gain spectrum of experimental works taken from [8]. In contrast, the black and gray solid curves without dots are the simulation findings in this work. The black curve is the gain with a pump dithering while the gray curve is the gain without the pump dithering.

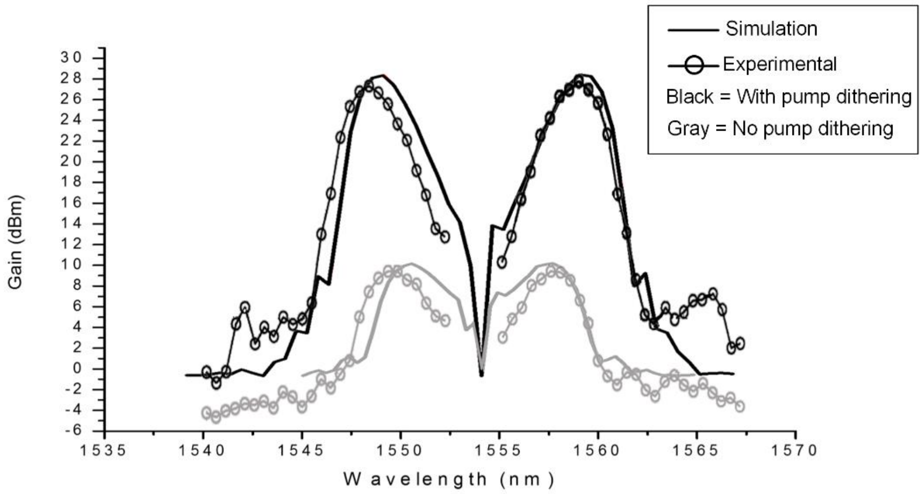

Figure 2. Gain for cascaded FOPA with pump dithering (black curve) and without pump dithering (gray curve). The solid curves are the results from simulation; while the curves with dots are the results taken from ref [8]

The simulation results obtained are almost similar to the experimental results taken from ref [8]. The simulated gain with and without pump dithering are 27 dB and 9 dB, respectively. Meanwhile, the simulated bandwidth with and without pump dithering are 20 nm and 12 nm, respectively. The gain and bandwidth for cascaded FOPA with a pump dithering are higher than the cascaded FOPA without pump dithering. The pump dithering has suppressed the SBS by dithering the pump light. The pump linewidth is broadened and increase the SBS threshold. The maximum power of the pump is delivered to the HNLF. The gain for both cases shows a good agreement and the investigation at the output power at each stage is conducted. The investigation is continued by observed the signal power at each stage. The signal power at each stage is crucial as the gain is observed the signal power at the input and output. Figure 3 shows the signal power at each stage of cascaded FOPA without a pump dithering.

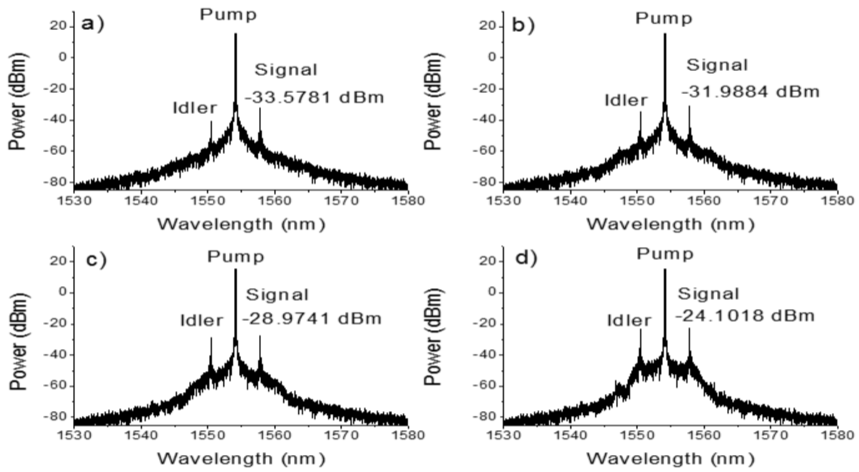

Figure 3. The output of every stage (no pump dithering)

As can be seen in Figure 3, the signal wavelength, λ_s is 1557.8 nm. Meanwhile the first idler wavelength, λ_1 is at 1550.4nm. The signal power at the first stage is -33.5781 dBm as shown in Figure 3(a). The signal power at the second stage of cascaded FOPA without the pump dithering is -31.9884 dBm as shown in Figure 3(b). Subsequently, the power is amplified with a signal power achieved -28.9741 dBm as shown in Figure 3(c). At the last stage, the signal power is -24.1018 dBm as shown in Figure 3(d). Then, the cascaded FOPA with a pump dithering is investigated by placing a 300 MHz RF-tone at the pump. Figure 4 shows the output at each stage for cascaded FOPA with a 300 MHz RF-tone.

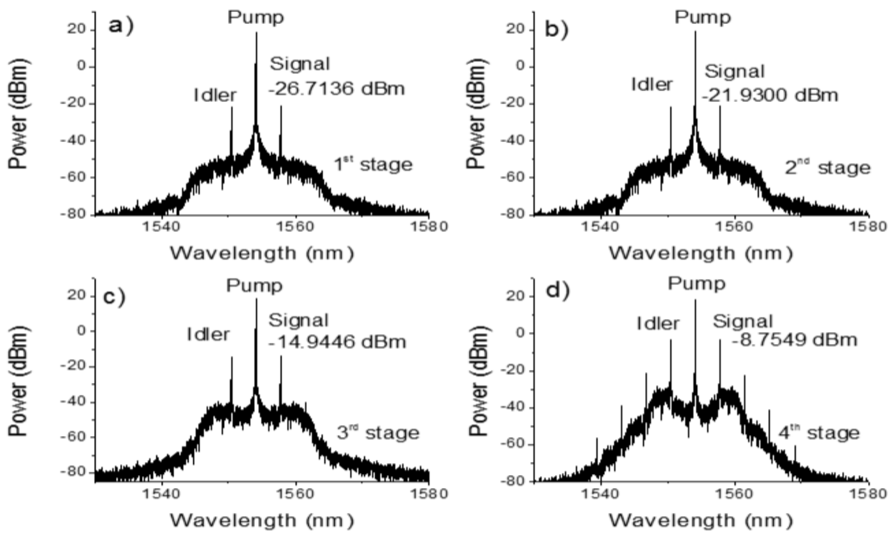

Figure 4. The output at every stage of cascaded FOPA (with pump dithering)

Figure 4 shows the output at each stage of the cascaded FOPA with a pump dithering. At the first stage, the signal power reached -26.7136 dBm as shown in Figure 4(a). Figure 4(b) indicates the result at the second stage where the idler power increases to -21.9300 dBm. The increasing signal power is also observed at the next stages as the third stage and the fourth stage signal power are -14.9446 and -8.7549 dBm as can be seen in Figure 4(c) and Figure

4(d). The signal power of the cascaded FOPA with a pump dithering at every stage is higher than the signal power of the cascaded FOPA without a pump dithering. This shows a good agreement with the gain spectrum as the power is amplified inside the cascaded FOPA. Table 2 states the signal powers at every stage for both cases.

Table 2. The signal powers at every stage for cascaded FOPA with and without pump dithering

Stage	No pump dithering (dBm)	With pump dithering (dBm)
1st stage	-33.5781	-26.7316
2nd stage	-31.9884	-21.9300
3rd stage	-28.9741	-14.9446
4th stage	-24.1018	-8.7549

The pump and idler powers are also examined. Table 3 shows the pump power and idler powers for the both cases. The pump decreases at every stage for both cases. This is due to the optical power transfer from the pump to the signal and idler. The pump power at each stage for cascaded FOPA with a pump dithering is higher than the cascaded FOPA without a pump dithering. The idler power is also increases at every stage for both cases due to power transfer from the pump. The effect of pump dithering in cascaded FOPA has been compared and it clearly shows that pump dithering also affects the pump and idler power.

Table 3. The pump and idler powers at each stage for both cases

Stage	No pump dithering (dBm)		With pump dithering (dBm)	
	Pump power	Idler power	Pump power	Idler power
1st stage	15.9437	-39.1205	19.2852	-28.9943
2nd stage	15.8205	-32.8605	19.1614	-21.7156
3rd stage	15.6798	-27.5765	19.0162	-14.0660
4th stage	15.4827	-21.7035	18.7543	-3.8718

5. Conclusion

In conclusion, the pump dithering improves the gain and bandwidth of the cascaded FOPA. The gain is enhanced from 9 dB to 27 dB while the bandwidth is broadened from 12 nm to 20 nm. The pump dithering suppresses the SBS by increasing the pump linewidth. The characteristics at each stage also shown an improvement where the signal power at each stage is growing. The signal power at every stage is low when there is no pump dithering. At the final stage of cascaded FOPA, the signal power is -8.7549 dBm with a pump dithering and -24.1018 dBm without a pump dithering.

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