Investigation on gain characteristics in non-degenerate cascaded phase sensitive parametric amplifiers*

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(Received 25 December 2011)

We theoretically and experimentally show the impact of the ratio between the signal and idler generated from the PIA part on the gain characteristics in the continuous wave (CW) pump non-degenerate cascaded phase-sensitive fiber optical parametric amplifier (PS-FOPA). The results show that the length of highly nonlinear fiber (HNLF) used for generating the idler can cause the variation of power ratio between the idler and signal, which significantly affects the gain characteristics of the PS-FOPA under the small signal gain condition. To obtain high gain, it is better to choose long HNLF to generate idler. In our experiment, 5.5 dB gain and 18 nm bandwidth (on/off gain>10 dBm) in PS-FOPA can be achieved when 300 m-long HNLF instead of 200 m-long HNLF is used in PIA.

Document code: A **Article ID:** 1673-1905(2012)03-0172-4

DOI 10.1007/s11801-012-1174-4

The performance of FOPA has been greatly improved[1-4]. In recent years, the phase-sensitive fiber optical parametric amplifiers (PS-FOPAs) have attracted great interest because it can provide noise figure (NF) less than 3 dB[5]. The non-degenerate PS-FOPA is widely used because it can be compatible with the wavelength-division multiplexing (WDM) operation[6] and used to compress the phase noise applied in the signal regeneration in the optical transmission systems[7-9].

The frequency non-degenerate PS-FOPA in the dispersion shift fiber was firstly experimentally demonstrated in 2005 by Vasilyev[10]. A novel scheme for generating the pump and idler optical waves aligned to an input signal carrier for phase sensitive amplification was demonstrated[11]. The bandwidth and noise figure in single or dual pump non-degenerate PS-FOPA were also investigated[12-14]. However, recently most investigations are focused on the noise of the non-degenerated PS-FOPA.

In this paper, we theoretically and experimentally show the impact of the ratio between the signal and idler generated from the PIA part on the gain characteristics in continuous wave (CW) pump non-degenerate cascaded PS-FOPA. In experiments, the HNLFs with the lengths of 200 m and 300 m are used. By comparing the gain characteristics when different lengths of the fiber are chosen in PIA, it can be found that it is better to select longer HNLF in PIA to obtain higher gain and wider bandwidth.

The basic equations for describing the process of FOPA in terms of optical power and phase are as follows[9]:

$$\frac{\mathrm{d}P_\mathrm{p}}{\mathrm{d}z} = -\alpha P_\mathrm{p} - 4\gamma\left(P_\mathrm{p}^2 P_\mathrm{s} P_\mathrm{i}\right)^{\frac{1}{2}}\sin\theta\,, \tag{1}$$

$$\frac{\mathrm{d}P_\mathrm{s}}{\mathrm{d}z} = -P_\mathrm{s} + 2\gamma\left(P_\mathrm{p}^2 P_\mathrm{s} P_\mathrm{i}\right)^{\frac{1}{2}}\sin\theta\,, \tag{2}$$

$$\frac{\mathrm{d}P_\mathrm{i}}{\mathrm{d}z} = -\alpha P_\mathrm{i} + 2\gamma\left(P_\mathrm{p}^2 P_\mathrm{s} P_\mathrm{i}\right)^{\frac{1}{2}}\sin\theta\,, \tag{3}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}z} = \Delta\beta + \gamma\{2P_\mathrm{p} - P_\mathrm{s} - P_\mathrm{i} + [(P_\mathrm{p}^2 P_\mathrm{s}/P_\mathrm{i})^{\frac{1}{2}} + (P_\mathrm{p}^2 P_\mathrm{i}/P_\mathrm{s})^{\frac{1}{2}} - 4(P_\mathrm{s}P_\mathrm{i})^{\frac{1}{2}}]\cos\theta\}\,, \tag{4}$$

where P_p, P_s and P_i are the optical powers for pump, signal and idler, respectively. α is the linear loss coefficient of the gain fiber. $\gamma=2\pi n_2/\lambda A_\mathrm{eff}$ is the nonlinear coefficient, where n_2 and A_eff are the fiber's nonlinear index and effective mode

* This work has been supported by the National Basic Research Program of China (Nos.2010CB327605 and 2010CB328300), and the Specialized Research Fund for the Young Scholars Program of Beijing University of Posts and Telecommunications (Nos.2011RC0309 and 2011RC008).

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area, respectively. $\Delta\beta=\beta_s+\beta_i-2\beta_p$ is the linear phase mismatch per unit length among the signal, idler and pump. The relative phase difference is

$$\theta(z)=\Delta\beta z+\phi_s(z)+\phi_i(z)-2\phi_p(z), \quad (5)$$

where ϕ_s, ϕ_i and ϕ_p are the phases of the signal, idler and pump, respectively.

The schematic PS-FOPA model includes three parts as shown in Fig.1. The first part is a segment of HNLF used as a PIA, in which the signal is amplified and the idler is generated. The second part is used to process the relative phase relationship among the pump, signal and idler. The third part is used as a PSA when the processed signal, pump and idler are launched into the HNLF at the same time.

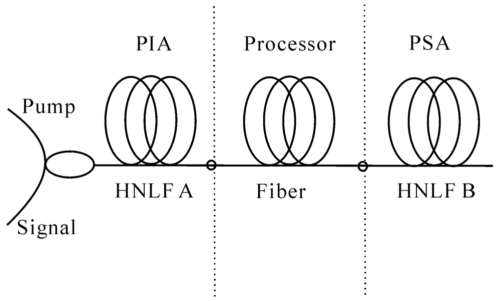


Fig.1 Schematic model of PS-FOPA

In the case of non-degenerate cascaded PS-FOPA, the idler is generated and the signal is amplified in the PIA. The power ratio $\eta^{\mathrm{PIA}2}\equiv P_i/P_s=\frac{G_i}{1+G_i}\cdot\frac{P_{i0}}{P_{s0}}$ between the idler and the signal depends on the gain characteristics of PIA. The relative phase difference $\theta^{\mathrm{PIA}}=\phi_s^{\mathrm{PIA}}+\phi_i^{\mathrm{PIA}}-2\phi_p^{\mathrm{PIA}}$ of the three waves depends on the phase-matching of PIA.

The second part acts as an optical processor, where the phase relationship and the power ratio can be changed. In this model, a segment of fiber is used in the second part. The signal, pump and idler are input into the PSA after propagating through the second part. We have $|\omega_s-\omega_p|=|\omega_p-\omega_i|<<\omega_p$, $\Delta\beta\approx\beta_2(\omega_s-\omega_p)^2$, where ω_p, ω_s and $\omega_i=2\omega_p-\omega_s$ are the angular frequencies of pump, signal and idler, respectively, and β_2 is the group-velocity dispersion coefficient of the fiber. At the input of the PSA, the relative phase difference θ^{PSA} and power ratio η^{PSA} can be expressed as

$$\theta^{\mathrm{PSA}}(\omega)=\theta^{\mathrm{OP}}(\omega)=\theta^{\mathrm{PIA}}(\omega)+\Delta\beta L_{\mathrm{OP}}\approx\theta^{\mathrm{Out-PIA}}(\omega)+\beta_2(\omega_s-\omega_P)^2L_{\mathrm{OP}}, \quad (6)$$

$$\eta^{\mathrm{PSA}}(\omega)=\eta^{\mathrm{OP}}(\omega)=\left(\frac{P_i^{\mathrm{OP}}(L_{\mathrm{OP}})}{P_s^{\mathrm{OP}}(L_{\mathrm{OP}})}\right)^{\frac{1}{2}}=\left(\frac{P_i^{\mathrm{OP}}(0)\exp(\alpha(\omega_i)L_{\mathrm{OP}})}{P_s^{\mathrm{OP}}(0)\exp(\alpha(\omega_s)L_{\mathrm{OP}})}\right)^{\frac{1}{2}}=\zeta\eta^{\mathrm{PIA}}, \quad (7)$$

where L_{OP} is the length of the fiber and ζ is the power ratio coefficient caused by the fiber attenuation. When $|\omega_s-\omega_i|<<\omega_p$, $\zeta\approx1$. The superscripts in Eqs.(6) and (7) are used to distinguish the locations in the cascaded PS-FOPA.

When only the PSA section is taken into consideration, an analytical solution for the gain of the PSA-FOPA can be obtained as follows[9]:

$$G_{\mathrm{PSA}}(\theta^{\mathrm{PSA}})=1+\left\{1+\frac{4\gamma^2P_p^2\eta^{\mathrm{PSA}\,2}+\kappa^2+4\gamma\kappa P_p\eta^{\mathrm{PSA}}\cos(\theta^{\mathrm{PSA}})}{4g^2}\right\}\sinh^2(gL)+\frac{\gamma P_p\eta^{\mathrm{PSA}}\sin(\theta^{\mathrm{PSA}})}{g}\sinh(2gL), \quad (8)$$

where $\kappa=\Delta\beta+2\gamma P_p$ is the net phase mismatch, and $g=[(\gamma P_p)^2-(\kappa/2)^2]^{\frac{1}{2}}$ is the parametric-gain coefficient. θ^{PSA} is the relative phase difference and η^{PSA} is the power ratio, which can be obtained from Eqs.(1) and (7). The simulation results are shown in Fig.2.

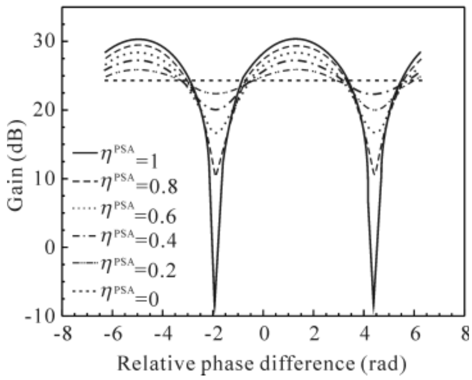


Fig.2 Relationship between the gain and the relative phase difference as the power ratio is changed

In Fig.2, when the idler generated from PIA is input into the fiber together with the pump and signal, the power flow depends on the relative phase difference θ^{PSA} among the three waves. For $\theta=\pi/2$, the power can be transferred from the pump to the signal and idler, and the parametric amplification takes place. For $\theta=-\pi/2$, the power can be transferred from the signal and idler to the pump, and the parametric de-amplification takes place. Therefore, the gain is modulated by the relative phase difference. However, the power ratio between the signal and idler also affects the gain characteristics as seen from Fig.2. When $\eta^{\mathrm{PSA}}=0$, there is no idler, and the system works as PIA, where the gain is constant. As the η^{PSA} increases, the gain dependence on the relative phase difference significantly increases. The variation of gain curve is around the gain of the PIA.

The experimental setup for non-degenerate cascaded PS-FOPA is shown in Fig.3. A tunable laser (TL1) serves as the pump. In order to increase the pump power, the phase modulator driven by multi-tones radio frequencies (RF) is used to suppress the stimulated Brillioun scattering (SBS)[15,16], and an EDFA is used to boost the pump power. After the pump is amplified by the EDFA, we introduce an optical band pass filter (OBPF) with a full-width at half-maximum (FWHM) of 0.9 nm to filter the ASE noise caused by the EDFA. Another tunable laser (TL2) is used as the signal. The signal is input into the cascaded PA-FOPA together with the processed pump. In order to obtain the highest gain, the polarization controllers (PCs) are used to maintain the relative state of polarization (SOP) of the signal and the pump. The gain characteristics of the cascaded PS-FOPA are monitored by optical power meters (OPMs) and optical spectra analyzer (OSA) via 10 dB couplers, respectively. In the cascaded PS-FOPA experimental setup, we use three segments of fiber. The first and third segments are the same highly nonlinear fiber (HNLF), where the zero dispersion wavelength (ZDW) is λ_0=1553 nm, the effective area is A_{eff}=9.5 μm^2, the dispersion slope at 1550 nm is about 0.02 ps•km^{-1}•nm^{-2}, and the attenuation at 1550 nm is about 0.6 dB/km. The second segment of the fiber is a standard single mode fiber (SMF-28) with a length of 2 m. The pump power at the input of the PIA part is a constant of ~ 28 dBm and the wavelength of the pump is set at 1554 nm.

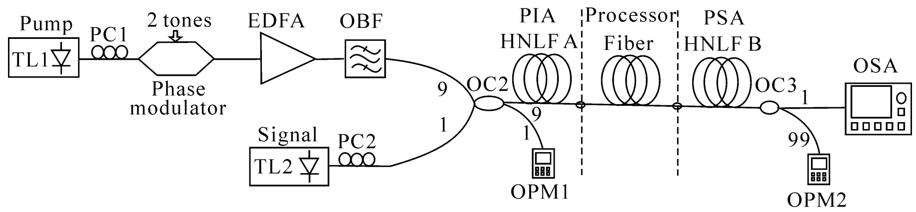
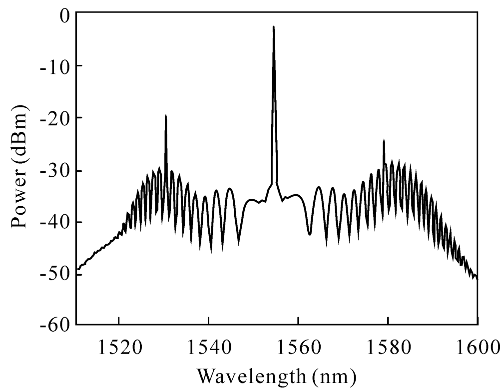
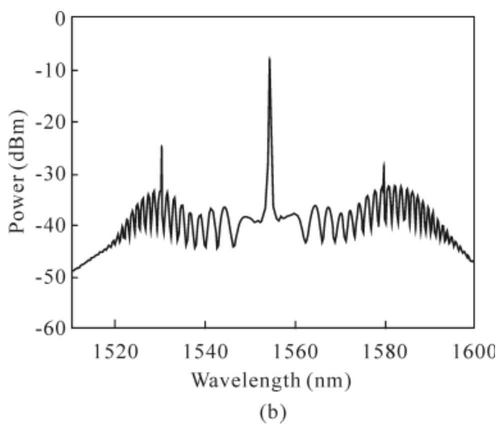


Fig.3 Experimental setup of the non-degenerate cascaded PS-FOPA

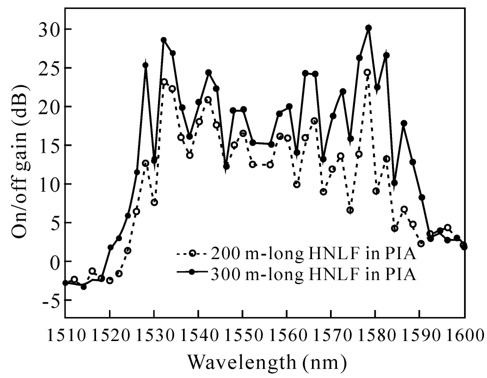
As a small signal with the wavelength of λ_s=1530 nm is launched into the PS-FOPA, the output spectra are shown in Fig.4. At the output of the PIA, the power ratio depends on the gain of the PIA. When longer HNLF is used, the power ratio between the idler and the signal at the output of the PIA is larger. Therefore, we can get higher gain and larger fluctuation of spectrum as the longer HNLF is used.



(a)



(b)



(c)

Fig.4 Spectra in the PS-FOPA: (a) 300 m-long HNLF for PIA; (b) 200 m-long HNLF for PIA; (c) Gain spectrum

The on/off gain of the non-degenerate cascaded PS-FOPA is obtained as illustrated in Fig.4(c). In the case of 300 m-long HNLF, the maximum gain is 29.83 dB and the bandwidth is 74 nm (on-off gain>10 dBm). In the case of 200 m-long HNLF, the corresponding maximum gain is 24.32 dB and the bandwidth is 56 nm (on-off gain>10 dBm). The higher gain and wider bandwidth can be obtained as the longer HNLF is used, which agrees well with the simulation results. We can also find that the fluctuation in the case of 300 m-long HNLF is larger than that in the case of 200 m-long HNLF. Thus, the power ratio between the idler and the signal from PIA significantly affects the gain spectrum of the cascaded PS-FOPA. By optimizing the length of HNLF used in PIA, we can improve the gain characteristics of the non-degenerate cascaded phase sensitive parametric amplifiers.

In conclusion, the effects of the power ratio between the idler and signal and the relative phase difference of the input waves on the gain characteristics of the non-degenerate cascaded PS-FOPA are studied. The results show that not only the relative phase difference but also the power ratio significantly affects the maximum gain and the fluctuation of the gain spectra. 5.5 dB gain and 18 nm bandwidth can be obtained when 300 m-long HNLF instead of 200 m-long HNLF is used in PIA. The maximum gain is 29.83 dB and the bandwidth is 74 nm (on-off gain>10 dBm) when the 300 m-long HNLF is used. By optimizing the length of HNLF used in PIA and PSA, the PS-FOPA with high on-off gain and large bandwidth can be obtained.

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