Theoretical and Simulation Analysis of the Fiber Optical Parametric Amplifier (FOPA) with Cascaded Structure

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Zhefeng Hu
University of Electronic Science and Technology of China

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<Jie Gao*, Yongsheng Cao, Fushen Chen, Bao Sun, Zhefeng Hu>
School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu, 611731

ABSTRACT

A novel scheme is proposed to obviously improve the amplified gain, gain flatness and bandwidth characteristics of FOPA by applying a cascaded fiber structure. The basic structure of the cascaded fiber optical parametric amplifier (CFOPA) is introduced. Then, the expression of signals pass gain characteristic is obtained by utilizing a set of coupled equations. The gain, bandwidth and gain flatness characteristics of the CFOPA with the different parameters of DCF, such as fiber length l', dispersion slope $dD'/d\lambda$, and so on, are theoretical analyzed and optimized. Furthermore, simulation analysis is applied to verify the theoretical results by using Optisystem 7.0 software. Although, there are a few deviations between the simulation and the theoretical results, the simulation results effectively demonstrate the validity and feasibility of the theoretical analysis.

Key words：FOPA, CFOPA, gain, bandwidth, gain flatness

1. INTRODUCTION

Optical amplifier is an important part of the all-optical communication system; meanwhile, it promotes the development of the optical multiplexing, optical soliton communication and all-optical networks. In recent decades, with the rapid development of information and communication technology, high-gain and wide-bandwidth optical amplifier also promotes the process of the optical fiber communication systems into the direction of high speed, high capacity and long distance transmission. With the rapid development of dense wavelength division multiplexing (DWDM) technology, optical communication system has put forward higher requirements for optical amplifiers. Recently, a novel optical amplifier technology which is based on nonlinear optical amplification effect--the fiber optical parametric amplifier (FOPA) has attracted much attention [1], due to its large optical gain (the parametric gain is exponentially proportional to the applied pump power in the case of small signal approximation), wide gain bandwidth (arbitrarily optical wavelength could be effectively amplified) and phase-sensitive property (noise-free optical amplification could be achieved, i.e. 0-dB noise figure) [2-3]. However, there are some deficiencies in the simple FOPA, such as gain is not high enough, flat-gain characteristic is poor, and so on.

In this paper, we propose a novel scheme to obviously improve the amplified gain, gain flatness and bandwidth characteristics of FOPA, by applying a cascaded fiber structure. In our proposal, the dispersion compensating fibers

***E-mail: gscj123@126.com; Telephone: 15882156310**

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(DCFs) have the negative chromatic dispersion are located among the high-nonlinearity optical fiber (HNLFs), thus, the DCFs could compensate the chromatic dispersion of HNLFs and obtain better gain characteristics [4-5].

This paper, firstly, the gain expression of the cascaded fiber optical parametric amplifier (CFOPA) is obtained by applying a set of coupled equations. According to the expression, the signal pass gain, the gain bandwidth and the gain flatness characteristics of the CFOPA are optimized by theoretical analysis. Finally, computer simulation is utilized to verify the theoretical results.

2. THEORY

The basic structure of the cascaded fiber with DCFs and HNLFs is shown in Fig.1.

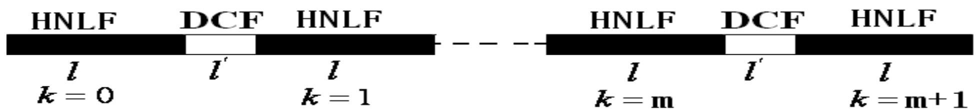


Fig.1 The basic structure of the cascaded fiber

The total length of the HNLF is L and it is divided into m+1 sections with an equal length $l=L/(m+1)$. In the proposal, m section DCFs, each of length l', which could compensate the chromatic dispersion effect periodically and enhance the CFOPA gain performances, are inserted uniformly into the m+1 section HNLFs.

For convenience of analysis, we discuss the CFOPA in a degenerated case with one pump source, an optical signal, and an idler, with respective angular frequencies w_p, w_s, and w_i. All fields are in the same state of linear polarization [6].

If the fiber loss is neglected, the electric field phasor of the pump E_p, signal E_s and idler E_i in the first section HNLF could be presented by the following coupled equations:

$$\frac{dE_s}{dz} = (i\beta_s + 2i\gamma P_P)E_s + i\gamma E_p^2 E_i^* \tag{1}$$

$$\frac{dE_i}{dz} = (i\beta_i + 2i\gamma P_P)E_i + i\gamma E_p^2 E_s^* \tag{2}$$

Where z is the distance from the beginning of the first section HNLF, $P_p=|E_p|^2$ is the pump power at z.

Then letting

$$E_p = F_p e^{i\beta_p z} \tag{3}$$

$$E_s = F_s e^{i\beta_p z} \tag{4}$$

$$E_i = F_i e^{i\beta_p z} \tag{5}$$

Assuming that the pump is not depleted by the nonlinear process, which means F_p is the only subject to self-phase modulation. Hence, $P_k=P_0 = P_p$ (k=1, 2…m+1), so (1) and (2) become

$$\frac{dF_s}{dz} = \left[i\left(\beta_s - \beta_p\right) + 2i\gamma P_p\right]F_s + i\gamma P_p e^{2i\gamma P_p Z} F_i \tag{6}$$

$$\frac{dF_i}{dz} = \left[i\left(\beta_i - \beta_p\right) + 2i\gamma P_p\right]F_i + i\gamma P_p e^{2i\gamma P_p Z} F_s \tag{7}$$

Where β is the propagation constant in the HNLF, γ is the nonlinearity coefficient of the HNLF.

Upon passage through the DCF, the $F'(l)$ is transformed into

$$F_P^{/}(l) = F_P(l) e^{i\Phi_p^{/}} \alpha^{1/2} \tag{8}$$

$$F_s^{/}(l) = F_s(l) e^{i\Phi_s^{/}} \alpha^{1/2} \tag{9}$$

$$F_i^{/}(l) = F_i(l) e^{i\Phi_i^{/}} \alpha^{1/2} \tag{10}$$

Where $\Phi^{/}_p=0$, $\Phi^{/}_s=(\beta^{/}_s-\beta^{/}_p)l^{/}$, $\Phi^{/}_i=(\beta^{/}_i-\beta^{/}_p)l^{/}$, $\beta^{/}$ is the propagation constant in the DCF, $\alpha=10^{-0.2Ls}$ is the transmittance through two splices, Ls is the power loss.

Based on the Eq. (8) and Eq. (9), the inputs of the second HNLF $F^{/}_s(l)$ and $F^{/}_i(l)$ could be obtained. By iterating this procedure, the electric field phasor at the output of a periodic sequence of (m+1) section HNLF is obtained. Consequently, signal gain G_s of CFOPA is expressed as

$$G_s = \frac{1}{1-a^2}\left\{v_{33}\sin\left[(m+1)\cos^{-1}a\right] - \sin\left[m\cos^{-1}a\right]\right\}^2 \tag{11}$$

Where

$$v_{33} = e^{i\Phi^{/}/2}(\cosh gl + \frac{ik}{2g}\sinh gl) \tag{12}$$

and

$$a = \cos gl \cos\Phi^{/}/2 - \frac{k}{2g}\sinh gl \sin\Phi^{/}/2 \tag{13}$$

Where $\Phi^{/}$ is the phase shift in the DCF and $\Phi^{/}=\Delta\beta^{/}l^{/}$, the phase mismatch $\Delta\beta^{/}$ in the DCF is given by

$$\Delta\beta^{/} = \beta^{/}(w_s) + \beta^{/}(w_i) - 2\beta^{/}(w_p) = -\frac{2\pi c}{\lambda_0^2}\frac{dD^{/}}{d\lambda}(\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2 \tag{14}$$

Here, $dD^{/}/d\lambda$ is the slope of the dispersion at the zero-dispersion wavelength in the DCF and λ_0 is the zero-dispersion wavelength in the DCF. The parametric gain coefficient g is given by

$$g^2 = (\gamma p_p)^2 - (k/2)^2 = -\Delta\beta[\frac{\Delta\beta}{4} + \gamma p_p] \tag{15}$$

Here, the phase mismatch $\Delta\beta$ in the HNLF is given by

$$\Delta\beta = \beta(w_s) + \beta(w_i) - 2\beta(w_p) = -\frac{2\pi c}{\lambda_0^2}\frac{dD}{d\lambda}(\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2 \quad (16)$$

Here, k is the phase mismatch parameter in the HNLF, it is described as

$$\frac{d\theta}{dz} \approx \Delta\beta + \gamma(2p_p - p_s - p_i) \approx \Delta\beta + 2\gamma p_p = k \quad (17)$$

3. THEORETICAL ANALYSIS

According to the Eq. (11), setting the parameters of the HNLF as shown in Table I, and the power of pump source P_p =7 W at λ_p=1550 nm, the length of DCF l'=5 m, dispersion slope of DCF $dD'/d\lambda$=-0.10 ps/nm^2 km. The signal pass gain characteristics of CFOPA as a function of input signal wavelength, with different section number m are theoretical measured in Fig.2.

Table I. The parameters of the HNLF

Length (m)	40
Zero-dispersion wavelength (nm)	1550
Dispersion slope (ps/nm^2/km)	+0.03
Nonlinear coefficient (W/km)	14

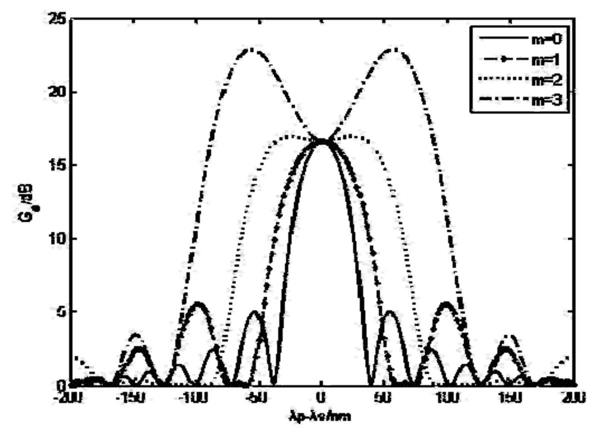
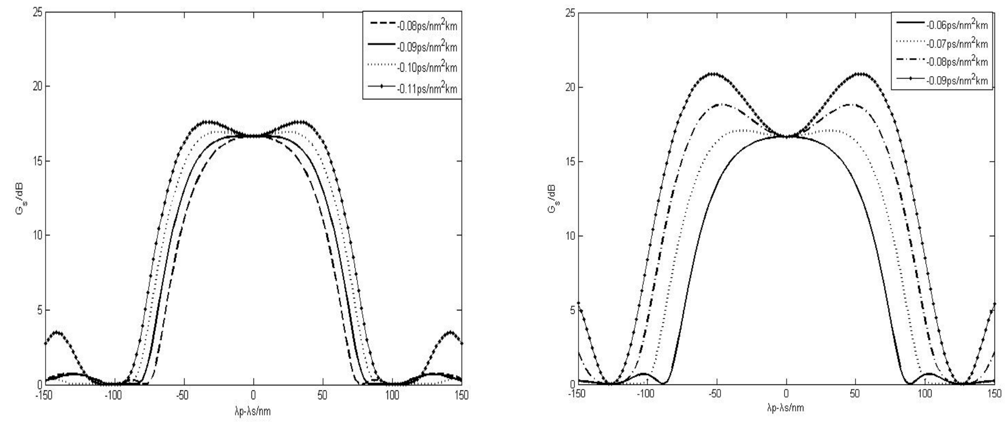


Fig. 2 The signal pass gain of CFOPA as a function of input signal wavelength with different m

Defining the gain bandwidth is that the G_s is larger than 5 dB as $B_{>5\,dB}$, and the deviation between the peak gain and the gain at λ_p-λ_0=0 as the gain flatness F.

It can been seen from Fig. 2, if the section number m increases, the CFOPA signal peak gain will become higher and the $B_{>5\,dB}$ becomes larger. The peak gain reaches 22.84 dB and the $B_{>5\,dB}$ reaches 220 nm when m=3, and the peak gain is 16.9 dB and the $B_{>5\,dB}$ is 150 nm when m=2. Therefore, increasing m could enhance the CFOPA signal peak gain and the bandwidth characteristics. Besides, the gain flatness is also affected by m, and when m is 2 and 3, F is 0.3 and 6.2 dB, respectively. Therefore, increasing section number m could improve the signal gain of CFOPA, but the gain flatness is debased.

Based on Eq. (11), CFOPA signal pass gain characteristics as a function of input signal wavelength, with different dispersion slope of DCF $dD^{/}/d\lambda$ are theoretical measured when m=2 and m=3, respectively, in Fig. 3, and here choosing a length of inserted DCF $l^{/}$=5 m.



(a) (b)

Fig. 3 The signal pass gain of CFOPA as a function of input signal wavelength with different $dD^{/}/d\lambda$: (a) m=2; (b) m=3

Based on the curves in Fig. 3, the measured results are listed in Table II and Table III.

Table II. The measured results when m=2

$dD'/d\lambda$ (ps/nm^2 km)	Peak gain (dB)	$B_{>5dB}$ (nm)	F (dB)
-0.08	16.64	125	0
-0.09	16.64	137	0
-0.10	16.88	146	0.26
-0.11	17.60	160	0.95

Table III. The measured results when m=3

$dD'/d\lambda$ (ps/nm^2 km)	Peak gain (dB)	$B_{>5dB}$ (nm)	F (dB)
-0.06	16.64	148	0
-0.07	17.06	174	0.41
-0.08	18.78	198	2.14
-0.09	20.87	210	4

The results in Table II and Table III indicate that increasing the dispersion slope of DCF could enhance the CFOPA signal gain and gain bandwidth, The peak gain reaches 17.60 dB and the $B_{>5\ dB}$ reaches 160 nm when m=2 and $dD'/d\lambda$=-0.11 ps/nm^2 km, and the peak gain is 20.80 dB and the $B_{>5\ dB}$ is 210 nm when m=3 and $dD'/d\lambda$=-0.09 ps/nm^2 km. Therefore, increasing $dD^{/}/d\lambda$ could enhance the CFOPA signal peak gain and the bandwidth characteristics. The gain flatness F increases with the absolute value of the $dD^{/}/d\lambda$, in other words, the gain flatness becomes poor with the growth of the absolute value of the $dD^{/}/d\lambda$. Therefore, it is need to sacrifice gain and bandwidth to get good gain flatness.

CFOPA signal pass gain characteristics as a function of input signal wavelength, with different length of inserted DCF $l^{/}$ are theoretical measured in Fig. 4, here choosing m=3 and $dD'/d\lambda$=-0.07 ps/nm^2 km.

According to the results in Fig. 4, the signal pass gain and gain bandwidth characteristics of CFOPA with different length of inserted DCF are shown in Table IV.

As known from Table IV, the gain ,bandwidth and flatness increase with the length of inserted DCF, the peak gain reaches 17.46 dB, the $B_{>5\ dB}$ reaches 180 nm and the gain flatness reaches 0.82 dB when $l^{/}$=5.2 m. Increasing the length of inserted DCF could enhance the CFOPA signal gain and bandwidth, but the gain flatness becomes poor with the increase of $l^{/}$.

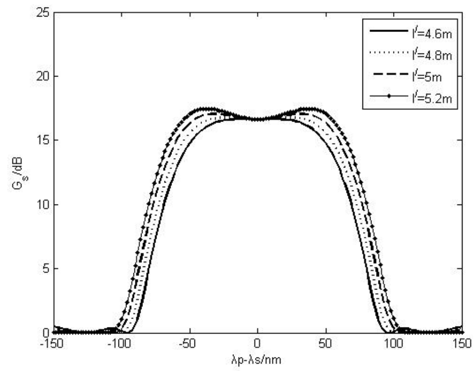


Fig. 4 The signal pass gain of FOPA as a function of input signal wavelength with different length of inserted DCF

Table IV. The measured results with different length of inserted DCF

$l^{/}$ (m)	Peak gain (dB)	$B_{>5dB}$ (nm)	F (dB)
4.6	16.56	158	0.12
4.8	16.77	166	0.13
5	17.06	174	0.42
5.2	17.46	180	0.82

4. SIMULATION ANALYSIS

A simulation setup of the CFOPA in the degenerated case with one pump is shown in Fig. 5, and Optisystem 7.0 software is utilized for the simulation purposes. As seen from Fig. 5, a high power pump at λ_p=1550 nm is generated by a pump source, a small input signal at λ_s ranging from 1400 nm to 1700 nm is generated by a signal source, the linewidths of the pump source and signal source are 10 MHz, a 3 dB coupler is applied to combine the pump beam and the signal beam. The cascaded fiber which is formed by DCFs and HNLFs is employed to amplify the input signal. The parameters of the HNLF are shown in Table I, and choosing the parameters of the DCF as a group of optimized ones, which are analyzed in theory, that is m=2, dispersion slope is -0.07 ps/nm^{2}km and the length is 5 m; an optical band-pass filter (OBPF) is applied to extract the amplified signal beam, the central wavelength of the OBPF is corresponding with the wavelength of the signal source; an optical spectrum analyzer is applied to check the amplified signal beam [7-8]. The simulation results are shown in Fig. 6.

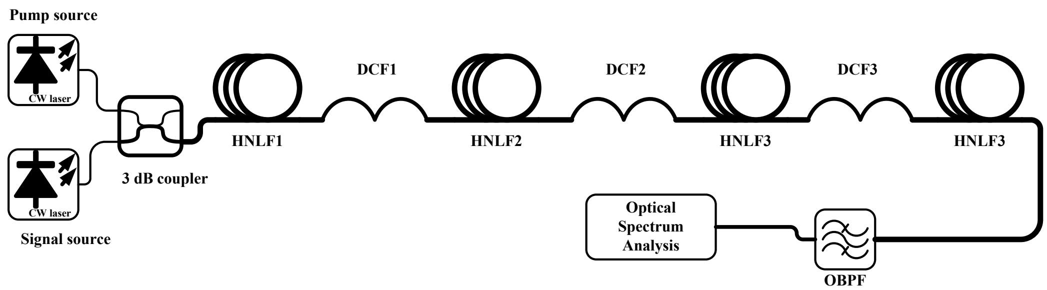


Fig. 5 Simulation setup of the proposed CFOPA

Simulation results in Fig. 6 demonstrate the theoretical analysis of the CFOPA signal pass gain and gain bandwidth characteristics. For simulation results, the peak gain is 12.4 dB, $B_{>5\,dB}$ is 80 nm and F is 0.3 dB. The simulation curve is similar with the theoretical one, although there are some deviations. The reason why these deviations occur is that the theoretical analysis is under an ideal condition, that means many parameters in simulation analysis debase the CFOPA performance, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), fiber loss, and so on.

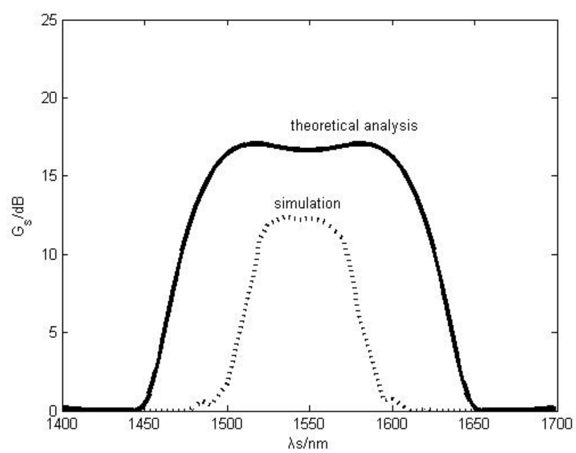


Fig. 6 The simulation and theoretical results of the proposed CFOPA

5. CONCLUTION

Based on the coupled equations, the theoretical gain expression of CFOPA is derived. According to the gain expression, the signal pass gain, the gain bandwidth and the gain flatness characteristics of CFOPA are optimized by theoretical analysis.

Simulation setup is constructed in Optisystem 7.0 software to verify the theoretical results, by using the optimal theoretical parameters. Although there are some deviations, the simulation results effectively demonstrate the validity and feasibility of the theoretical analysis.

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