Gain characteristics of a dual-pump fiber optical parametric amplifier with Raman effect*

ZANG Ke(臧可)**, **YU Chong-xiu**(余重秀), **SANG Xin-zhu**(桑新柱), **LIU Meng**(刘勐), **RAO Lan**(饶岚), and **WANG Kui-ru**(王葵如)

Key Laboratory of Information Photonics and Optical Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China

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We investigate the pump-depleted model of a dual-pump fiber optical parametric amplifier (FOPA) with Raman effect. As bandwidth increases, the gain profile of the distorted FOPA would be impacted seriously. Under the widebands, especially when the pump separation is large, zero dispersion wavelength (ZDW) fluctuation is another factor which can not be neglected. Numerical simulations with these comprehensive factors are mainly analyzed to obtain their influence on gain characteristics. Saturated gain spectrum is also discussed in detail.

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Fiber optical parametric amplifer (FOPA)[1] can provide more competitive advantages, such as wideband amplification, low noise figure and signal regeneration. FOPA applied in crystal fiber is also a promising device due to its large nonlinearity, convenience for integration[2]. The theory and experiment have demonstrated that the dual-pump FOPA is able to provide a relatively flat gain over a wider wavelength range than the single-pump FOPA. When considering large gain bandwidth, Raman effect leads to a gain profile deviation from that only considering FOPA gain[3]. Besides, the Raman effect would be coupled into thermal phonons of Stokes and anti-Stokes waves, which results in an asymmetric Raman-induced noise figure[4]. Early efforts were made to develop analytic expressions for small-signal gain combined with Raman effect in single-pump parametric amplifier[5]. Recently, a 155 nm-gain distortion induced by Raman effect in dual-pump FOPA was experimentally observed[6]. And the dual-pump model with Raman effect was given[7]. Theoretical analyses and experimental results agreed well, but it is still an approximation of an imperfect model which assumes pump power is always far greater than that of signal and idler. It neglected the interaction among pump, signal and idler. By taking account of the equations in the dual pump FOPA[8] and the Raman-assisted parametric gain, a full model was revised from Ref.[9]. It involved the pump depletion effect and the interaction among pump, signal and idler. In order to obtain a high saturated gain experimentally, the pump power can be increased. The other way is increasing the length of highly nonlinear fiber (HNLF). But the two ways both have some shortages for realizing saturation.

In this paper, we propose a revised full model of dual-pump FOPA combined with Raman effect. And we numerically solve propagation equations by taking account of Raman gain and FOPA gain under depleted pump power condition to show the gain characteristics in a dual-pump FOPA. Meanwhile, other factors, such as ZDW fluctuation and saturated FOPA effect, are also included in the simulation, which can provide guidances for experiments to some extent.

In the approximation of collinearly polarized monochromatic waves, the nonlinear polarization can be given by

$$P^{(3)}(z,t) \propto (1-f)A(z,t)\int_{-\infty}^{+\infty}\delta(t-\tau)\,|\,A(z,\tau)\,|^2\,\mathrm{d}\tau + fA(z,t)\int_{-\infty}^{t}h_{\mathrm{R}}^{(3)}(t-\tau)\,|\,A(z,t)\,|^2\,\mathrm{d}\tau\ , \qquad (1)$$

where $A(z,t)$ is the field amplitude, $\delta(t\text{-}\tau)$ is an electronic response which is much shorter than 1 fs, $h_{\mathrm{R}}^{(3)}(t\text{-}\tau)$ is the nuclear

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** E-mail: 514956891@qq.com

vibrational response for the Raman effect, which is a time-delayed Raman response of about 50 fs, and f accounts for the fractional Raman contribution, which is found to be about 0.18 in silica fibers[10]. The evolution processes of the pump fields A_1 and A_2, signal field A_s and idler field A_i along the highly nonlinear fiber with Raman effect can be described by the following pump-depleted propagation equations as

$$\frac{\mathrm{d}A_1}{\mathrm{d}z}=-\frac{\alpha}{2}A_1+\mathrm{i}[\gamma|A_1|^2A_1+\phi_1(z)A_1+2\gamma\{1-f+\frac{f}{2}(H(\omega_s-\omega_2)+H(\omega_i-\omega_2))\}A_sA_iA_2^*\exp(\mathrm{i}\Delta\beta z)]\ , \quad (2)$$

$$\frac{\mathrm{d}A_2}{\mathrm{d}z}=-\frac{\alpha}{2}A_2+\mathrm{i}[\gamma|A_2|^2A_2+\phi_2(z)A_2+2\gamma\{1-f+\frac{f}{2}(H(\omega_s-\omega_1)+H(\omega_i-\omega_1))\}A_sA_iA_1^*\exp(\mathrm{i}\Delta\beta z)]\ , \quad (3)$$

$$\frac{\mathrm{d}A_s}{\mathrm{d}z}=-\frac{\alpha}{2}A_s+\mathrm{i}[\gamma|A_s|^2A_s+\phi_s(z)A_s+2\gamma\{1-f+\frac{f}{2}(H(\omega_1-\omega_i)+H(\omega_2-\omega_i))\}A_1A_2A_i^*\exp(-\mathrm{i}\Delta\beta z)]\ , \quad (4)$$

$$\frac{\mathrm{d}A_i}{\mathrm{d}z}=-\frac{\alpha}{2}A_i+\mathrm{i}[\gamma|A_i|^2A_i+\phi_i(z)A_i+2\gamma\{1-f+\frac{f}{2}(H(\omega_1-\omega_s)+H(\omega_2-\omega_s))\}A_1A_2A_s^*\exp(-\mathrm{i}\Delta\beta z)]\ , \quad (5)$$

$$\phi_1=(2-f)\gamma(|A_2|^2+|A_s|^2+|A_i|^2)+f\gamma(H(\omega_1-\omega_2)\times|A_2|^2+H(\omega_1-\omega_s)|A_s|^2+H(\omega_1-\omega_i)|A_i|^2)\ , \quad (6)$$

$$\phi_2=(2-f)\gamma(|A_1|^2+|A_s|^2+|A_i|^2)+f\gamma(H(\omega_2-\omega_1)|A_1|^2+H(\omega_2-\omega_s)|A_s|^2+H(\omega_2-\omega_i)|A_i|^2)\ , \quad (7)$$

$$\phi_s=(2-f)\gamma(|A_1|^2+|A_2|^2+|A_i|^2)+f\gamma(H(\omega_s-\omega_1)|A_1|^2+H(\omega_s-\omega_2)|A_2|^2+H(\omega_s-\omega_i)|A_i|^2)\ , \quad (8)$$

$$\phi_i=(2-f)\gamma(|A_1|^2+|A_2|^2+|A_s|^2)+f\gamma(H(\omega_i-\omega_1)|A_1|^2+H(\omega_i-\omega_2)|A_2|^2+H(\omega_i-\omega_s)|A_s|^2)\ , \quad (9)$$

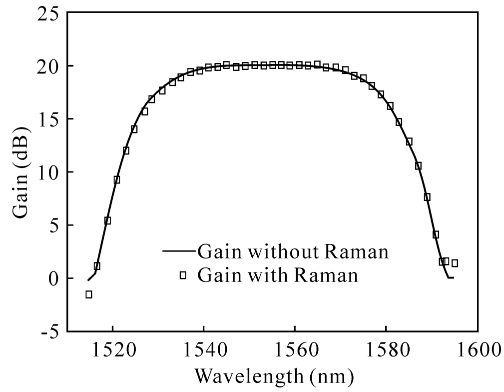
$$H(\omega)=\int_{-\infty}^{\infty}h_R^{(3)}(t)\exp(\mathrm{i}\omega t)\,\mathrm{d}t\ , \quad (10)$$

$$\Delta(\beta)=2\sum_{m=1}^{\infty}\frac{\beta_{2m}}{2m!}\left[(\Delta\omega_s)^{2m}-(\Delta\omega_p)^{2m}\right]\ , \quad (11)$$

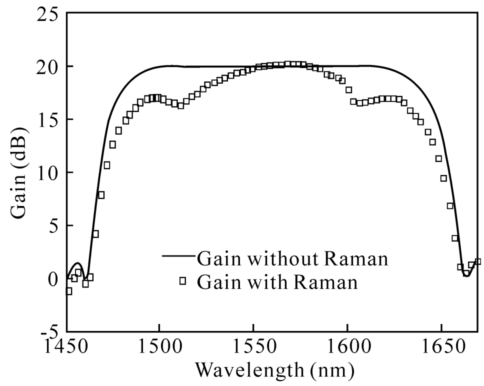
where $\omega_c=(\omega_1+\omega_2)/2$, $\Delta\omega_s=\omega_s-\omega_c$, $\Delta\omega_p=(\omega_1-\omega_2)/2$, and $H(\omega)$ is the Raman response function expressed as the form of angular frequency.

The gain medium chosen in numerical simulation is a 140 m-long highly nonlinear fiber with the nonlinear coefficient of $\gamma=11\ \mathrm{km}^{-1}\cdot\mathrm{W}^{-1}$, the ZDW of $\lambda_0=1555.8$ nm and the attenuation of $\alpha=0.5$ dB/km. At the same time, we assume the third order dispersion is $\beta_3=3.8\times10^{-41}$ s/m, and the fourth order dispersion is $\beta_4=2.3\times10^{-56}$ s/m.

Pump power is set as P_1=1.2 W (short wavelength) and P_2=0.8 W (long wavelength). In the subsequent simulations, 48 nm-pump separation represents the pump wavelengths centered at 1530 nm and 1578 nm, while 160 nm-pump separation means a pump combination of 1480 nm and 1640 nm. Once we take account of Raman effect into an FOPA, a higher gain on the long wavelength side and a lower gain on the opposite side are observed[11]. Here we compare the gain profiles with and without Raman effect under the two different gain bandwidths as shown in Fig.1. It is clearly seen from Fig.1 that the asymmetric gain profile appears. Raman-induced gain distortion is relatively small when the bandwidth is not large enough to allow signal to enter the main response range of Raman effect (100 nm away from pumps). Fig.1(b) shows the biggest distortion which is due to the fact that the FOPA gain is totally overlapped by the Raman effect.



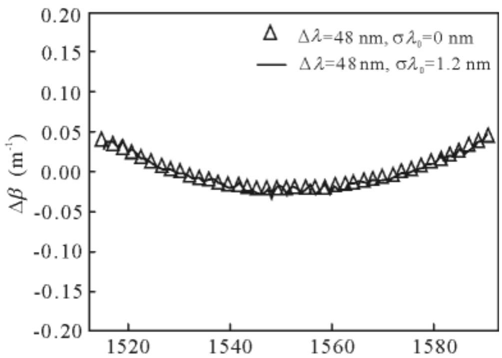
(a) 48 nm-pump separation



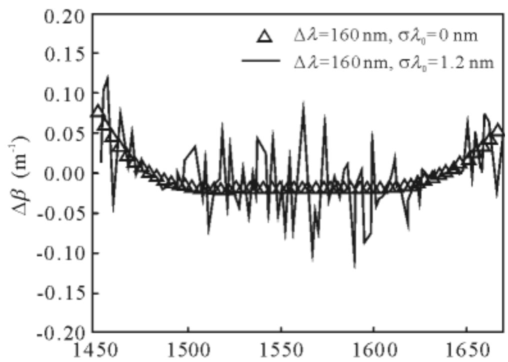
(b) 160 nm-pump separation

Fig.1 Dual-pump gain spectra without and with Raman effect

The gain spectrum of dual-pump FOPA is affected by the frequency dependent $\Delta\beta$. Eq.(11) shows the linear phase mismatch expanded in a Taylor series around the frequency of ω_c. By utilizing a relatively large pump separation and making the central frequency close to the zero dispersion frequency of ω_0, we can get a fairly flat gain profile over a wide wavelength range. But in fact, the random ZDW fluctuation along the fiber leads to the random variation of linear phase mismatch, which is illustrated in Fig.2. Large wavelength separation between the two pumps increases amplifier bandwidth; on the other hand, it turns out to bring less tolerance of dispersion fluctuation. Gain spectrum becomes highly nonuniform for a given FOPA because of such a dispersion fluctuation[12]. The random coefficient of ZDW can be generated in a Fourier series[13]. Fig.2(b) shows that the case of 160 nm separation is in good phase matching condition with a large wavelength range from 1490 nm to 1630 nm. Outside this range, it is in the phase mismatching condition. Both linear phase mismatch coefficients in phase matching and mismatching areas are strongly affected by 1.2 nm ZDW fluctuation. However, the FOPA with 48 nm pump separation experiences a relatively slight effect brought by the same ZDW standard deviation.



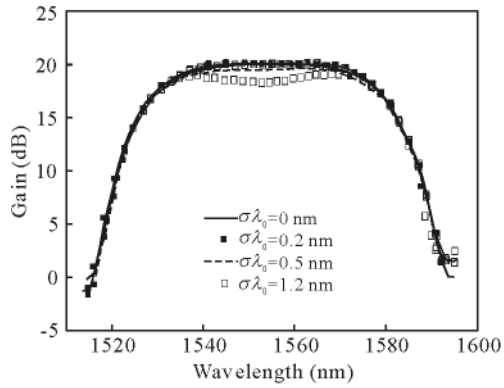
(a) 48 nm-pump separation



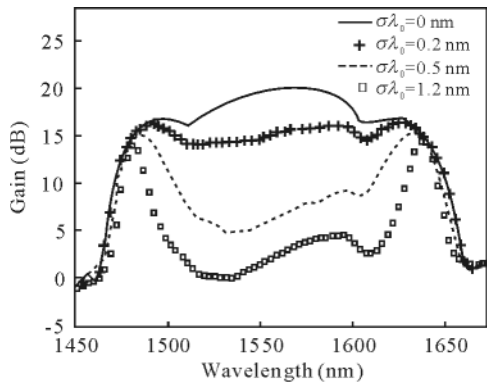
(b) 160 nm-pump separation

Fig.2 Variations of linear phase mismatch caused by ZDW fluctuation

The previous study on the gain performance due to ZDW fluctuation did not take account of Raman effect[14]. The distorted gain profiles combining Raman effect and ZDW fluctuation are shown in Fig.3. Similarly, we can see from Fig.3 that 160 nm-pump separation brings a more severe deterioration on the gain spectra compared with 48 nm-pump separation where gain profile remains nearly consistent. All the shown signal gains are averaged in the calculation. Fig.3(b) also shows the two obvious spectral dips approximately 120 nm away from the pumps, resulting from Raman effect. Besides, it is noted that small ZDW fluctuations are beneficial to obtain a flat gain spectrum.



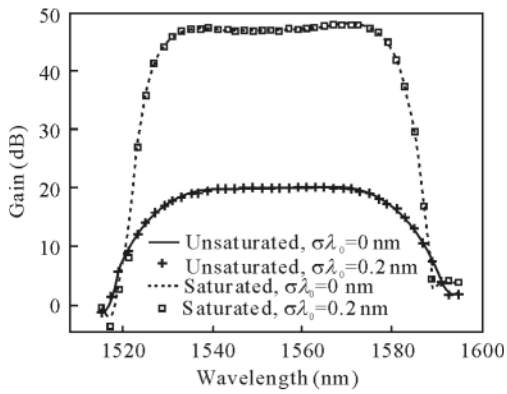
(a) 48 nm-pump separation



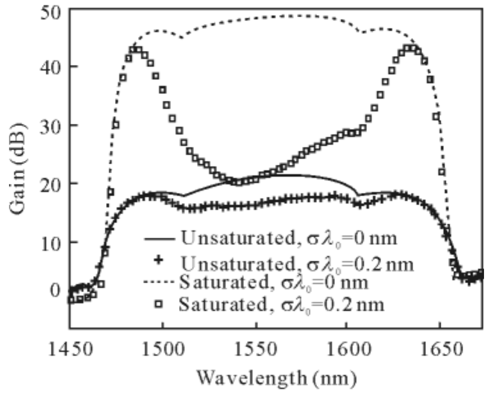
(b) 160 nm-pump separation

Fig.3 Distorted gain profiles combining Raman effect and ZDW fluctuation

To observe saturated parametric amplification with Raman effect, we try to get the numerical solution of Eqs. (2) to (5) by setting the length of HNLF at 340 m. The signal is amplified along the fiber till it becomes gain saturation. A nearly 50 dB peak gain can be seen in Fig.4 when the saturation of signal gain occurs without considering any ZDW variation. We assume a 0.2 nm ZDW fluctuation in the following cases of 140 m-long HNLF and 340 m-long HNLF.



(a) 48 nm-pump separation



(b) 160 nm-pump separation

Fig.4 Gain spectra of saturated and unsaturated parametric amplification with Raman effect

Under the assumption of the same 0.2 nm ZDW fluctuation and 160 nm-pump separation, a relatively flat saturated gain profile as expected appears only in the case of 140 m-long fiber, due to a bigger deviation accumulates along the 340 m-long fiber.

By increasing fiber length, a wide and high gain profile can experience more severe ZDW influence, which leads to a relatively small saturated gain. Another simple way is to increase pump power to achieve saturation. We give a new set of parameters of 160 nm-pump separation, P_1=3 W, P_2=2 W, and L=140 m. Simulation result is shown in Fig.5. Generally, EDFA can boom the pump to a high power. It can also bring a large amplified spontaneous emission (ASE) noise. Moreover, the stimulated Brillouin scattering threshold also limits the input power coupled into the fiber.

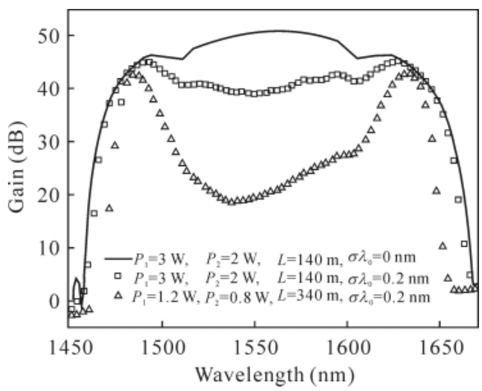


Fig.5 Saturation induced by increasing pump power or HNLF length

In summary, we have numerically solved the pump-depleted model of a dual-pump fiber optical parametric amplifier combined with the effect of Raman. Comprehensive analyses about gain characteristics are presented as well. Calculation shows that there are a higher gain on long wavelength side and a lower gain on short wavelength side. Spectrum dips about 120 nm deviated from pump center wavelength are also clearly observed in simulations. Furthermore, the distorted gain profile is susceptible to ZDW fluctuation, particularly when bandwidth is large enough or signal gain is in the state of saturation. Increasing pump power can obtain a relatively high saturated gain. But it is hard to couple strong power with high optical signal-to-noise ratio (OSNR) into HNLF. On the other hand, the way to achieve saturation by increasing fiber length would experience more sever ZDW influence, which leads to a relatively low saturated gain. All these results provide guidance of designing broadband dual-pump FOPA for future experimental work.

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