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Ultra-flat and broadband two-pump optical parametric amplifiers using a single-section highly nonlinear fiber

Yu Tian *, Xiaosheng Xiao, Shiming Gao, Si Lu, Changxi Yang

State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing 100084, China

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Abstract

A broadband two-pump optical parametric amplifier with ultra-flat gain spectra is proposed in a single-section highly nonlinear fiber. By elaborately setting the dispersions and pump wavelength space, a gain over 250 nm with 0.02-dB uniformity is obtained. The pump polarizations and fiber length can be changed, achieving polarization-insensitive or higher gain, while the flatness and bandwidth of gain curve remain the same.

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1. Introduction

Fiber optical parametric amplifiers (FOPAs), based on highly efficient four-wave mixing, have been investigated since 1980s [1]. With the development of new high-power light sources and fibers with a nonlinear coefficient 5–10 times than conventional fibers, as well as the need of amplification outside the conventional erbium band, FOPAs have attracted a great deal of interest. As a promising technology for the future optical communication systems, it offers simultaneous possibilities of linear optical amplification with much broader bandwidth than erbium-doped fiber amplifiers (EDFAs) at arbitrary wavelength [2], low noise penalties lower than the 3-dB quantum limit [3], transparent wavelength conversion [4] and phase conjugation of the signals [5]. If the pump is intensity modulated, it can also be used for return-to-zero (RZ) pulse generation [6], optical sampling [7], or demultiplexing [8].

Early FOPAs were usually operated with one pulsed pump owing to its high peak power. However, pulsed pumps lead to no practical application because they require careful synchronization with data pulses. In comparison, FOPAs with one continuous-wave (CW) have many advantages. It is fully bit rate transparent, and the pump does not suffer from self-phase modulation (SPM) or induced cross-phase modulation (XPM). But at high average power level, stimulated Brillouin scattering (SBS) will occur [9]. It reduces the pump power going through the fiber. The most effective way to suppress SBS is to modulate the pump so that its spectrum is broadened much wider than the SBS gain width, which is typically several tens of megahertz [10]. Unfortunately, the idler spectrum is also broadened, sometimes can reach several gigahertz, which is too large for many applications.

FOPA driven by two pumps can solve the above problems. The need for enhancing SBS threshold is partially circumvented when the pump power is distributed between two pumps rather than concentrated in one. More importantly, two-pump FOPA offers additional degrees of design freedom to get a better performance [11,12]. For example,

* Corresponding author. Tel.: +86 10 62795433; fax: +86 10 62784503.
E-mail address: tianyu03@mails.tsinghua.edu.cn (Y. Tian).

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by controlling the relative phase of two pumps, one can suppress the idler broadening due to pump modulation. In the counter phase modulation scheme, two pumps are dithered with opposite phase, preserving their average frequency [13]. Using two orthogonal pump waves having different frequencies, the gain is almost insensitive to the polarization of the input signal [14,15]. Recently, a flat gain over 47 nm bandwidth was reported with two-pump FOPA [16].

Nevertheless, gains in most one- and two-pump configurations are not flat enough for WDM application owing to fiber dispersion characteristics, which fluctuates the phase match parameter. Many efforts have been made to solve the problem. For one-pump FOPA, a simple condition relating the second- and fourth-order dispersions was demonstrated which ensured flat and broadband gain spectra [17]. Its drawbacks are mentioned above as other one-pump FOPA. In Refs. [18–20], multi-section fibers with different zero-dispersion wavelengths (ZDW) and lengths were cascaded in both one- and two-pump schemes to realize flat gain. However, this method relied on precision balance between the pump power and the dispersion characteristics. ZDW and length, especially the ZDW of each section was required to meet the optimum value exactly, which was very hard to control for the differences were only few nanometers (or less). Cascaded sections also added more splice loss.

In this paper, an ultra-flat and broadband two-pump optical parametric amplifier based on single-section highly nonlinear fibers is presented. By elaborately setting the dispersions and pump wavelength space, a gain over 250 nm with 0.02-dB uniformity is obtained. Pump polarizations are flexible to be switched from parallel to orthogonal, and fiber length are tunable to achieve polarization-insensitive or higher gain, while the flatness and bandwidth of gain curve remain the same.

2. Theory

For FOPA with two parallel linear polarization pumps, four-wave mixing process is described by the following coupled wave equations [21]:

$$\mathrm{d}A_1/\mathrm{d}z = \mathrm{i}\gamma[|A_1|^2 + 2(|A_2|^2 + |A_3|^2 + |A_4|^2)]A_1 + 2\mathrm{i}\gamma A_2^* A_3 A_4 \mathrm{e}^{\mathrm{i}\Delta\beta z} \quad (1)$$

$$\mathrm{d}A_2/\mathrm{d}z = \mathrm{i}\gamma[|A_2|^2 + 2(|A_1|^2 + |A_3|^2 + |A_4|^2)]A_2 + 2\mathrm{i}\gamma A_1^* A_3 A_4 \mathrm{e}^{\mathrm{i}\Delta\beta z} \quad (2)$$

$$\mathrm{d}A_3/\mathrm{d}z = \mathrm{i}\gamma[|A_3|^2 + 2(|A_1|^2 + |A_2|^2 + |A_4|^2)]A_3 + 2\mathrm{i}\gamma A_1 A_2 A_4^* \mathrm{e}^{-\mathrm{i}\Delta\beta z} \quad (3)$$

$$\mathrm{d}A_4/\mathrm{d}z = \mathrm{i}\gamma[|A_4|^2 + 2(|A_1|^2 + |A_2|^2 + |A_3|^2)]A_4 + 2\mathrm{i}\gamma A_1 A_2 A_3^* \mathrm{e}^{-\mathrm{i}\Delta\beta z} \quad (4)$$

where A_1, A_2, A_3, and A_4 represent the amplitudes of pump1, pump2, signal, and idler, respectively; γ is the nonlinear coefficient of fibers; $\Delta\beta$ is the linear propagation-constant mismatch.

We define the central frequency as $\omega_c = (\omega_{p1} + \omega_{p2})/2 = (\omega_s + \omega_i)/2$, where ω_{p1}, ω_{p2}, ω_s, and ω_i represent the angular frequencies of pump1, pump2, signal, and idler, respectively. Assume that the pump powers are much more intensity than signal and idler; the pumps are not depleted, hence their powers, P_1 and P_2, remain constant. The gain parameter, g, is given by [22]

$$g^2 = (2\gamma\sqrt{P_1P_2})^2 - (\kappa/2)^2 \quad (5)$$

κ is the phase mismatch parameter, as is shown below [23]

$$\kappa = \beta_2[(\Delta\omega_s)^2 - (\Delta\omega_p)^2] + \beta_4[(\Delta\omega_s)^4 - (\Delta\omega_p)^4]/12 + \gamma(P_1 + P_2) \quad (6)$$

In Eq. (6), $\Delta\omega_s = \omega_s - \omega_c$, $\Delta\omega_p = \omega_{p_1} - \omega_c$, β_2 is the second-order dispersion at ω_c, β_4 is the fourth-order dispersion, regarded as a constant. Small-signal gain is written by

$$G(L) = 1 + (2\gamma\sqrt{P_1P_2}\sinh(gL)/g)^2 \quad (7)$$

L is the fiber length.

To achieve flat and broadband gain, two conditions must be met. Firstly, κ should be near some constant with low ripple over large-signal wavelength range. That means $\partial\kappa/\partial(\Delta\omega_s)$ must be small. Secondly, absolute value of this constant should be as small as possible, otherwise the gain may be too low to be practical. In a word, $|\kappa|$ must be close to zero with low ripple as $\Delta\omega_s$ increases. Eq. (6) shows that κ can be treated as a quadratic with $\Delta\omega_s^2$.

$$\kappa = \beta_4 y^2/12 + \beta_2 y + u \quad (8)$$

where $u = -\beta_4(\Delta\omega_p^4)/12 - \beta_2(\Delta\omega_p^2) + \gamma(P_1 + P_2)$ and $y = \Delta\omega_s^2$. $\partial\kappa/\partial y = 0$ happened at $y = -6\beta_2/\beta_4$. If we set $\kappa(y = -6\beta_2/\beta_4) = 0$, the two conditions mentioned above can be met simultaneously. We can get

$$\beta_2 = \frac{-\beta_4\Delta\omega_p^2 + [12\gamma(P_1 + P_2)\beta_4]^{1/2}}{6} \quad (9)$$

Substitute Eq. (9) in to Eq. (6), κ versus $\Delta\omega_s$ will be influenced by β_4, $\Delta\omega_p$, γ, and pump powers. Gain is also related to fiber length, L.

3. Results and discussion

Here, β_4 is chosen as 2.5×10^{-6} ps^4/km, which is the same order as Refs. [19,20]. Recently, Sumitomo has succeeded in fabricating a fiber with a very low value of β_4 [24], which is close to the value we used in this paper. When β_4 is selected, β_2 is determined by Eq. (9), thus ω_c, which depends on the second-order dispersion curve, is found. It has no effect on the shape of gain but the location of gain window (here we assume $\lambda_c = 2\pi c/\omega_c = 1550$ nm).

We set $L = 150$ m; $\gamma = 20$ W^{-1} km^{-1}; P_1 and P_2 are both 1 W, parallel linear polarization. Therefore, κ versus $\Delta\omega_s$ only depends on $\Delta\omega_p$. $\Delta\lambda_p = \lambda_c - \lambda_{p1}$ and $\Delta\lambda_p$ will be used later for convenience. The gain spectra of FOPA with different $\Delta\lambda_p$ are shown in Fig. 1. Obviously, the bandwidth grows as $\Delta\lambda_p$ increases, but the gain curve becomes uneven and occurs when $\Delta\lambda_p$ is too large. There exists an optimum value of $\Delta\lambda_p$ (here it is 150 nm). A 250 nm (from 1425 nm to 1675 nm) bandwidth gain over 45 dB with 0.02-dB

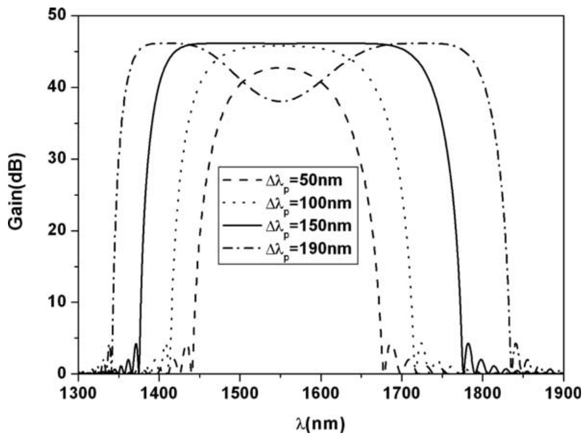

Fig. 1. Small-signal gain at the amplifier output with different $\Delta\lambda_p$.

uniformity is obtained. The ultra-flat broadband gain can be explained by the phase mismatch variation versus wavelength, as is indicated in Fig. 2. When $\Delta\lambda_p = 150$ nm, phase mismatch curve is nearly zero over a large wavelength range with little ripple.

In fact, the second-order dispersion β_2, or equivalently, ZDW does not remain constant. It fluctuates randomly along the amplifier length. Ref. [19] shows that the fluctuation of β_2 does not have much effect on the gain shape, provided that the average β_2 is maintained close to the optimum value. On the other hand, from experimental point of view, β_2, determined by Eq. (9), cannot be met accurately because of various uncertain factors such as laser wavelength dithering, which may affect the gain flatness. In our scheme, even if β_2 deviates from its ideal value within 30%, the shape of gain curve remains flat.

The gain spectra shown above are under the assumption that the input signal has the same linear polarization as two pumps. But in practical systems, polarization of input signal varies from time to time, which results in a polarization-dependent gain. When the polarizations of two pumps are set linearly orthogonal to each other at different frequencies, a polarization-insensitive gain is observed. In this scheme, Eqs. (5) and (7) are modified to the following expressions [22]:

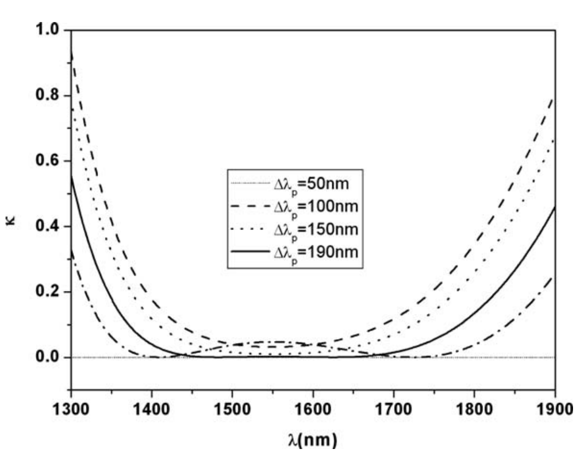

Fig. 2. Phase mismatch versus wavelength with different $\Delta\lambda_p$.

$$g^2 = (2\gamma\sqrt{P_1P_2}/3)^2 - (\kappa/2)^2 \quad (10)$$

$$G(L) = 1 + (2\gamma\sqrt{P_1P_2}\sinh(gL)/3g)^2 \quad (11)$$

Suppose the polarizations of the two pumps are linearly orthogonal, $\Delta\lambda_p = 150$ nm and other parameters are the same as mentioned above. Results are shown in Fig. 3. Although the gain is much lower than the parallel scheme, it is independent with the polarization of input signal. More interestingly, the bandwidth and uniformity of gain spectra keep the same as before. The gain versus fiber length, L, also exhibits the similar property with the parallel case, indicated in Fig. 4. As L increases, gain level is larger but bandwidth and flatness are not changed.

Therefore, we can get the following conclusion: in our scheme, the polarizations of the two pumps (parallel or orthogonal) and fiber lengths have little effect on the bandwidth and flatness of gain curve. Only the gain levels are different. This can be explained by phase match condition, for it is not changed during the tuning process. This flexible property will be very useful from the practical point of view. For one thing, the amplifier can be operated in two amplification modes, "polarization-sensitive higher gain" or "polarization-insensitive lower gain", with the same bandwidth and ultra-flat gain spectra. For another, ultra-

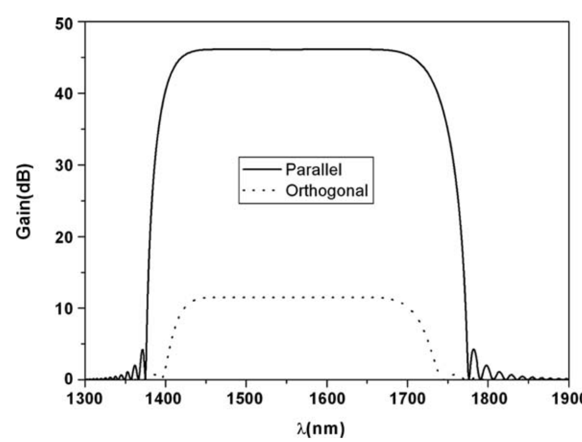

Fig. 3. Small-signal gain at the amplifier output with parallel and orthogonal polarization pumps.

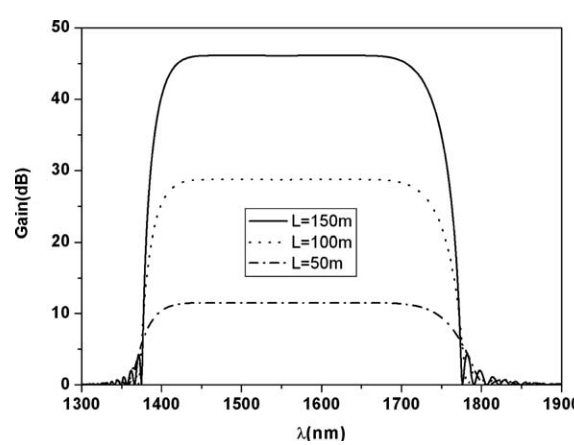

Fig. 4. Small-signal gain at the amplifier output with different fiber lengths.

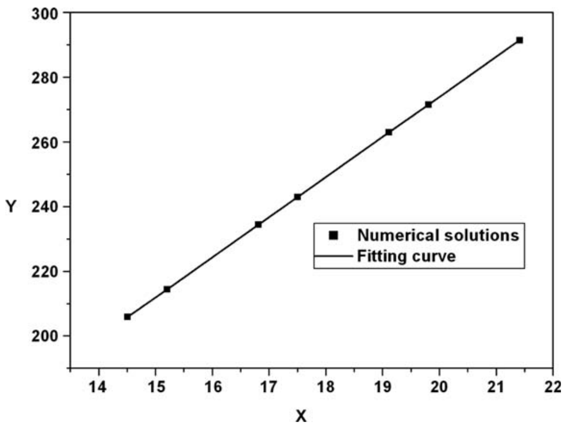

Fig. 5. Y versus X, fitting the constants of A and B.

flat amplifiers with different gain levels can be realized with the same coil of fiber. These cannot be achieved in the multi-section configuration, in which the pump polarizations, fiber length and ZDW of each fiber section will have a great effect on the gain value, bandwidth, and uniformity, thus should be balanced carefully with each other.

The discussions above are under the non-depletion assumption, in which pump power does not change along the fiber. Therefore, increase of fiber length results in unlimited growth of the gain. Also, the effect of input signal power on the gain is not considered in the simulation. In practical, as the fiber length and input signal power increase, more power will transmit from pump to signal and idler wave. Pump depletion cannot be neglected any more. Thus, the "ultra-flat and flexible" results are conditionally tenable. Similar to Ref. [17], we may also find an approximate expression for the fiber length, L_{lim}, which is defined as the maximum of fiber length, within which the pump depletion effect can be neglected. Under the pump non-depletion approximation, Eq. (8) and the optimum pump space discussed above are valid. Analytical solutions of Eqs. (1)–(4) are very complicated. Comparing Eqs. (1)–(4) with Eq. (5) in Ref. [17], we may predict that the L_{lim} in our FOPA scheme has the form as

$$L_{\mathrm{lim}} \approx \frac{1}{A\gamma P_0} \ln\left(B\frac{P_0}{P_{s0}}\right) \tag{12}$$

where A and B are constants. P_0 is the total power input and P_{s0} is the input signal power. Eq. (12) can be changed into $Y = CX + D$, where $X = \ln(P_0/P_{s0})$, $C = 1/(A\gamma P_0)$, $D = C\ln B$, $Y = L_{\mathrm{lim}}$. Solving Eqs. (1)–(4) numerically with different P_{s0}, the maximum pump depletion length is calculated. The results agree well with our prediction, as is shown in Fig. 5. The numerical results show that X and Y are linear relationship. A and B are fitted to be 2.0165 and 8.1179.

4. Conclusion

We demonstrated a broadband two-pump optical parametric amplifier with ultra-flat gain spectra using single-section highly nonlinear fibers. By elaborately setting the dispersions and pump wavelength space, a gain over 250 nm with 0.02-dB uniformity is obtained. Pump polarizations and fiber length can be tunable to meet different requirements such as polarization-insensitive or higher gain level, while the bandwidth and gain flatness are nearly kept unchanged. In the end, pump depletion effect is considered and applicability of the optimum values is discussed.

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