Optical parametric amplification in dual-pumped tellurite hybrid microstructured optical fiber with engineered chromatic dispersion

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Abstract. We numerically demonstrated broad and flattened gain spectra of optical parametric amplification employing highly nonlinear tellurite optical fiber and dual-pump configuration. The chromatic dispersion profile of the tellurite hybrid microstructured optical fiber was engineered to be near-zero and flattened, having four zero-dispersion wavelengths at 1421, 1643, 1928 and 2169 nm. The effect of pump wavelength was investigated when the two pump powers were kept at 1 W, the fiber length was 25 cm and the fiber nonlinearity was as high as 6642 W⁻¹km⁻¹. It is shown that OPA gain bandwidth with gain ripples could be as broad as 1393 nm at 10-dB signal gain. When the central pump wavelength approached the third zero-dispersion wavelength and the pump powers were 1.25 W, an ultra-flat (±0.01-dB gain fluctuation) and broad gain bandwidth (658 nm at 30-dB signal gain) could be achieved.

1. Introduction
Fiber optical parametric amplifiers (FOPAs) with flattened gain spectra and broad bandwidth are very promising for all-optical signal processing applications such as signal generation, broadband wavelength conversion, optical sampling, switching, wavelength division multiplexing (WDM), optical time division multiplexing (OTDM), etc [1-4]. Although a degenerate FWM configuration (single-pump) has been widely used for FOPA experiments, dual-pump FOPAs are now of great interest because they can present much broad and flattened gain spectra when the two pumps were tuned symmetrically to the zero-dispersion frequency (ω₀) of the fiber as first reported by Marhic et al [5]. There have been several efforts on dual-pump FOPA, both experimentally [6, 7] and numerically [2, 8, 9]. However, the performances are limited due to the uses of silica fibers. The low nonlinearity of silica fiber requires the fiber length of several kilometers to obtain practical FOPA gain and it is pointed that the fluctuation of zero-dispersion wavelength (ZDW) in such long fibers strongly affects FWM process [10-12]. Recently, much attention has been given to tellurite fibers due to their high nonlinearity, wide transmission windows and high glass stability [13]. But FOPAs in tellurite optical fibers are facing a great challenge because their ZDWs typically locate at long wavelengths far from the wavelengths of common and commercial pump sources. In order to control the dispersion of tellurite fibers with high

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freedom in telecommunication window, our group has developed hybrid microstructured optical fibers (HMOFs) whose refractive index difference ($\Delta n$) between core and cladding materials could be as large as 0.5. By using tellurite HMOF, a near-zero and flattened chromatic dispersion with four ZDWs was reported in [14] and a single-pump FOPA with broad gain bandwidth was demonstrated in [3].

In this paper, we present the simulated performance of dual-pump FOPA for tellurite HMOFs which have near-zero and flattened dispersion with four ZDWs. The effects of pump wavelengths and pump powers were investigated to achieve an ultra-flat and broad signal gain bandwidth.

2. Theory of dual-pump FOPA

The parametric signal gain ($G$) in dual-pump FOPA configuration is given by equation (1) [2].

$$G = 1 + \left( \frac{2\gamma\sqrt{PP_g}}{g} \right)^2 \sinh^2(gL)$$

where $g$ is the gain coefficient shown in equation (2), $\gamma$ is the nonlinear coefficient and $L$ is the fiber length.

$$g = \left[ (\gamma P_r r)^2 - \frac{1}{4}(\Delta \beta + \gamma P_p)^2 \right]^{1/2}$$

In equation (2), $P_p = P_1 + P_2$, $r = 2\sqrt{PP_g} / P_p$, $P_1$ and $P_2$ are pump powers at pump frequencies $\omega_s$ and $\omega_b$, respectively. As shown in Fig. 1, $\omega_s$ and $\omega_i$ are the signal and idler frequencies, respectively. They locate at the positions that the condition of $\omega_s + \omega_b = \omega_i + \omega_i$ is satisfied. The linear phase-mismatch $\Delta \beta$ in equation (2) is expressed by Eq. (3)

$$\Delta \beta = \beta_2 \left[ (\Delta \omega_s)^2 - (\Delta \omega_p)^2 \right] + \frac{1}{12} \beta_4 \left[ (\Delta \omega_s)^4 - (\Delta \omega_p)^4 \right] + \frac{1}{360} \beta_6 \left[ (\Delta \omega_s)^6 - (\Delta \omega_p)^6 \right]$$

where $\beta_2$, $\beta_4$ and $\beta_6$ are the second, the fourth and the sixth-order fiber dispersion coefficients. The frequency deviation between the signal frequency $\omega_s$ and the central frequency $\omega_c = (\omega_s + \omega_b) / 2$ is defined as $\Delta \omega_s = \omega_s - \omega_c$ while $\Delta \omega_p = (\omega_p - \omega_p) / 2$ is the half-frequency difference between the two pumps. Since the value of the gain coefficient $g$ depends on $\Delta \beta$, the signal gain $G$ depends on the phase-matching condition which is the key factor for efficient performance of FOPA. Broad gain bandwidth can be generated if the phase-matching condition given in equation (4) is satisfied [15].

$$\Delta \beta + \gamma (P_1 + P_2) = 0$$

3. Results and discussions

3.1. Tellurite HMOF and chromatic dispersion control

Figure 2 shows the microstructure of the proposed tellurite HMOF with a ring of six air holes in the cladding. It was designed with the core diameter ($D=0.8946 \ \mu m$), air hole diameter ($d=2.26 \ \mu m$) and the pitch which is the distance between the center of two adjacent air holes ($\Lambda=1.999 \ \mu m$). At 1550 nm,
the refractive indices of core and cladding were $n_{\text{core}}=2.058$ and $n_{\text{clad}}=1.568$ ($\Delta n=0.49$). The calculated nonlinear coefficient was as large as $\gamma=6642 \text{ W}^{-1}\text{km}^{-1}$. The full-vector finite element method (FEM) was applied to calculate the chromatic dispersion. In Fig. 3, a near-zero and flattened chromatic dispersion profile from 1.3 to 2.3 $\mu$m is shown with four ZDWs at 1421, 1643, 1928 and 2169 nm.

![Figure 2](image)

Figure 2. The design of tellurite HMOFs.

![Figure 3](image)

Figure 3. Chromatic dispersion of tellurite HMOFs

3.2. Numerical calculation of dual-pump FOPA in tellurite HMOF

All of the results in Figs. 4 and 5 were calculated when the two pump powers were the same $P_1=P_2=1$ W and the fiber length was $L=25$ cm. The signal gains were plotted as a function of signal wavelength. The symbols of square, circle and triangle corresponded to the pump wavelength A, B and the central C which are obtained from the pump frequencies $\omega_p$, $\omega_a$ and the central angular frequency $\omega_c$. The black, red and blue colors show different pump conditions. The gain bandwidths of each pump condition were determined in the shadowed range of the signal gain spectra. The details of pump wavelength conditions and gain bandwidths have been tabulated in Table 1.

![Figure 4](image)

Figure 4. The effects of pump wavelength on signal gain spectra and bandwidths for tellurite HMOF

![Figure 5](image)

Figure 5. The effects of pump wavelength on signal gain spectra and bandwidths for tellurite HMOF

![Figure 6](image)

Figure 6. The effects of pump power on signal gain spectra and bandwidths for tellurite HMOF

| Name | $\lambda_a$ (nm) | $\lambda_c$ (nm) | $\lambda_b$ (nm) | Bandwidth (nm) | Name | $\lambda_a$ (nm) | $\lambda_c$ (nm) | $\lambda_b$ (nm) | Bandwidth (nm) |
|------|----------------|----------------|----------------|--------------|------|----------------|----------------|----------------|--------------|
| F4.1 | 1607           | 1787           | 2013           | 1393         | F5.1 | 1555           | 1884           | 2392           | 694          |
| F4.2 | 1569           | 1788           | 2081           | 1385         | F5.2 | 1589           | 1906           | 2381           | 647          |
| F4.3 | 1544           | 1789           | 2126           | 1383         | F5.3 | 1623           | 1928           | 2376           | 645          |

Table 1. The pump wavelength conditions and corresponding gain bandwidths when $P_1=P_2=1$ W, $L=25$ cm and $\gamma=6642 \text{ W}^{-1}\text{km}^{-1}$

In Fig. 4, the calculated gain bandwidths of dual-pump FOPA which signal gains fluctuated from 13 to 23 dB were shown. At 10-dB signal gain, those bandwidths were very broad and could be 1393 nm for the pump condition F4.1. When the position of the pump $\lambda_a$ and $\lambda_b$ varied, the magnitude of gain fluctuation slightly changed but the shape of the gain spectra were kept. In contrast, flattened signal gain spectra could be found in Fig. 5. It is observed that when $\lambda_s$ approached the third ZDW, the parametric gain bandwidth reduced but the spectrum became flatter. The black, red and blue
spectra in Fig. 5 had ±0.1, ±0.01 and ±0.03-dB gain fluctuations, respectively. The bandwidth of the flat-gain region of the black (F5.1) was as broad as 694 nm which is much broader than those reported for most of highly nonlinear fibers so far [8, 9].

In Fig. 6, the effect of pump powers was studied for the black gain spectrum (F5.1) that was obtained in Fig. 5. The signal gain increased with the value of pump power. When $P_1 = P_2 = 1.25$ W, the gain flatness improved. An ultra-flat signal gain at 30 dB with ±0.01-dB gain fluctuation was obtained having 658-nm gain bandwidth from 1634 to 2292 nm. When $P_1 = P_2 = 1.5$ W, the signal gain could reach 37 dB, however, the gain spectrum was obtained with ±0.1-dB gain fluctuation. Another significant feature that could be noticed from Figs. 4, 5 and 6 is that very low values of the pump power were used for those calculations. It is attributed to the great contribution of the high nonlinearity and the near-zero and flattened dispersion profile of the proposed tellurite HMOF.

4. Conclusions

Highly nonlinear tellurite HMOFs were employed to study the performance of dual-pump FOPA by simulation. Due to the near-zero and flattened chromatic dispersion control from 1.3 to 2.3 µm with four ZDWs at 1421, 1643, 1928 and 2169 nm, broad and ultra-flat signal gain spectra could be realized for dual-pump FOPA. The results showed that when the central pump wavelength approached the third ZDW, an ultra-flat signal gain at 30 dB (±0.01-dB gain fluctuation) having broad gain bandwidth of 658 nm could be obtained. Moreover, the gain spectra with gain ripples could be as broad as 1390 nm at 10-dB gain. To the best of our knowledge, the potential, which is the ultra-flat and broad gain bandwidth of dual-pump FOPA using tellurite HMOF, has been reported for the first time with very low values of pump power.

Acknowledgments

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5. References

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