Suppressing the Effect of Dispersion Fluctuation on Broadband Optical Parametric Amplification using Highly Nonlinear Tellurite Microstructured Optical Fibers

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Keywords: Optical Parametric Amplification, Dispersion Fluctuation, Microstructured Optical Fiber, Highly Nonlinear Optical Fiber.

Abstract: The contribution of fiber nonlinearity to the signal gain spectrum of a fiber-optical parametric amplifier (FOPA) in presence of fiber transverse geometry variation is numerically studied in this work. This is the first time to demonstrate that the degradation of FOPA signal gain performance which is caused by fiber diameter fluctuation and zero-dispersion wavelength (ZDW) variation can be suppressed by using highly nonlinear optical fibers with short fiber length. By increasing the fiber nonlinear coefficient, the fiber length which is required to have similar value of signal gain is reduced, the signal gain bandwidth can be broadened and the spectral shape can be maintained. A tellurite microstructured optical fiber was fabricated by using a developed tellurite glass $78TeO_2$–$5ZnO$-$12Li_2O$-$5Bi_2O_3$ mol%. The fiber outer-diameter fluctuation is less than ±0.53 % and the corresponding ZDW varies less than ±2 nm over a 1-m-long section of the fabricated fiber. The fiber nonlinear coefficient is calculated to be 676 $W^{-1}km^{-1}$ which is 23 times larger than those values of highly nonlinear silica fibers. When the pump source is 5 W at 1557 nm, the influence of ZDW fluctuation on signal gain spectra is almost suppressed.

1 INTRODUCTION

With the explosive spread of telecommunication devices such as smartphones and computers in recent years, the amount of information travelling through the Internet is rapidly increasing and the demand for high transmission capacity over global telecommunication networks will continue to grow. Currently, wavelength division multiplexing (WDM) systems where different wavelengths propagate simultaneously in an optical fiber are used for multi-channel transmission. Although Erbium-doped fiber amplifiers (EDFA) are widely used as gain media for WDM systems, their gain bandwidths are as narrow as 30 nm from 1530 to 1560 nm (T. Jose, 2015). In order to expand the WDM operating range, fiber-optical parametric amplifiers (FOPAs) are very promising candidates because they can provide broad gain bandwidths and high signal gain in many spectral bands where conventional EDFAs cannot reach. FOPAs have been exploited for various applications such as signal amplification, wavelength conversion, phase-conjugation, slow and fast lights, optical signal processing and biomedical applications (M. E. Marhic, 2008).

The gain performance of FOPA is obtained by employing four-wave mixing (FWM) process in optical fibers. However, the phase-matching condition which determines FWM gain properties is very sensitive to the fluctuation of the chromatic dispersion and zero-dispersion wavelength (ZDW) which is caused by the fiber transverse geometry variation. As a result, it reduces the achievable parametric gain and gain bandwidth of FOPA and restricts practical applications of FOPA. The gain performances of FOPA in presence of dispersion fluctuation have been investigated by using conventional silica fiber. (M. Karlsson, 1998, M. Farahmand et.al, 2004, B. P. Kuo et.al, 2012). Due to their low nonlinearity, extremely long fibers (up to a few kilometres) are required to obtain proper values of parametric gain (G. Agrawal, 2007). In these configurations, the effect of ZDW fluctuation along the fiber length on FOPA gain spectra becomes significant and unavoidable.

Tuan, T., Harukata, K., Suzuki, T. and Ohishi, Y.
Suppressing the Effect of Dispersion Fluctuation on Broadband Optical Parametric Amplification using Highly Nonlinear Tellurite Microstructured Optical Fibers.
DOI: 10.5220/0006465800540058
In *Proceedings of the 14th International Joint Conference on e-Business and Telecommunications (ICETE 2017) - Volume 3: OPTICS*, pages 54-58
ISBN: 978-989-758-258-5

In this work, we proposed highly nonlinear tellurite microstructured optical fibers as promising candidates to shorten the required fiber length, and considerably suppress the influence of fiber transverse geometry variation and ZDW fluctuation on FOPA gain performance for more practical applications.

2 FIBER OPTICAL PARAMETRIC AMPLIFICATION

The gain performance of a single-pump FOPA configuration can be calculated by using the theory of a degenerated FWM process (G. Agrawal, 2007) whose phase-matching condition is given by Eq. (1)

$$\kappa = \Delta\beta + 2\gamma P \tag{1}$$

where P is the pump power, γ is the nonlinear coefficient and the linear phase-mismatch $\Delta\beta$ is defined by Eq. (2). Commonly, $\Delta\beta$ is calculated by introducing the Taylor series expansion up to the second term as in Eq. (3) where β_2 and β_4 are related to the dispersion parameter β_{30} and β_{40} calculated at the zero-dispersion frequency of the fiber as given in Eqs. (4) and (5) (G. Agrawal, 2007) and ω_p and ω_s are pump and signal frequencies, respectively.

$$\Delta\beta = \beta_i + \beta_s - 2\beta_p \tag{2}$$

$$\Delta\beta \approx \beta_2(\omega_s - \omega_p)^2 + \frac{1}{12}\beta_4(\omega_s - \omega_p)^4 \tag{3}$$

$$\beta_2 \approx \beta_{30}(\omega_p - \omega_0) + \frac{1}{2}\beta_{40}(\omega_p - \omega_0)^2 \tag{4}$$

$$\beta_4 \approx \beta_{40} \tag{5}$$

The optical signal gain (G_s) is calculated by Eq. (6) where L is the fiber length, $P_s(0)$ and $P_s(L)$ are the signal power at the input and output of the fiber and the parametric gain coefficient g is given by Eq. (7) (Hansryd et al., 2002)

$$G_s = \frac{P_s(L)}{P_s(0)} = 1 + (\frac{\gamma P}{g})^2 \sinh^2(gL) \tag{6}$$

$$g = \sqrt{(\gamma P)^2 - (\frac{\kappa}{2})^2} = \sqrt{(\gamma P)^2 - (\gamma P + \frac{\Delta\beta}{2})^2} \tag{7}$$

As an example, FOPA gain performance is investigated by using a 2.5-km-long fiber with the ZDW at 1550 nm such that β_{30} =0.1 ps^3/km and β_{40} =10^{-4} ps^4/km (G. Agrawal, 2007). The pump wavelength is λ_p =1550.2 nm, the pump power is P =1.2 W and the nonlinear coefficient is γ=2W^{-1}km^{-1}. The blue plot in Fig. 1 shows the gain spectrum calculated by using the above parameter.

Assuming that the ZDW does not locate at 1550 nm but has a random value in the range 1550 ±1 nm, the gain spectrum is modified and is plotted in Fig. 1 as shadow lines which show a considerable decrease in both signal gain and gain bandwidth. However, the distortion of FOPA signal gain spectra caused by the random ZDW-fluctuation is suppressed as can be seen in Fig. 2 when the nonlinear coefficient γ becomes 10 times larger than the value in Fig. 1. In addition, it is interesting to notice that the signal gain bandwidth is broadened and the fiber length L required to achieve similar parametric gain in Fig. 1 becomes 10 times shorter.

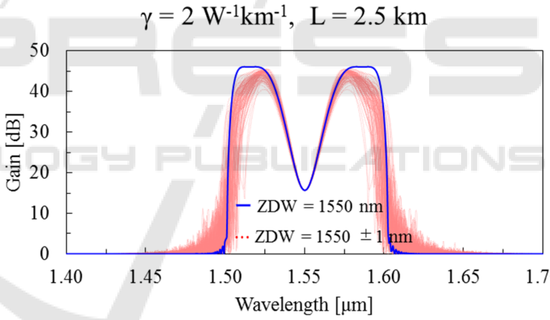

Figure 1: FOPA signal gain spectra with random ZDW-fluctuation (1550 ±1 nm) when γ=2 W^{-1}km^{-1} and L =2.5 km.

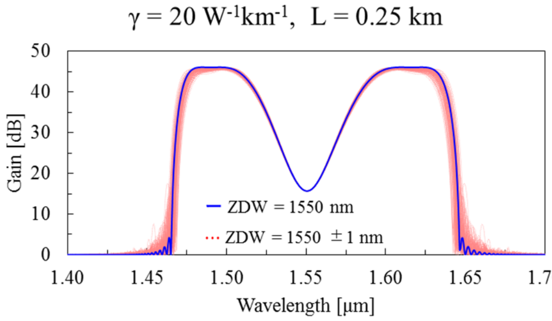

Figure 2: FOPA signal gain spectra with random ZDW-fluctuation (1550 ±1 nm) when γ=20 W^{-1}km^{-1} and L =0.25 km.

3 EFFECTS OF LONGITUDINAL FLUCTUATION IN THE ZERO-DISPERSION WAVELENGTH

3.1 Conventional Optical Fibers

To study FOPA performance in presence of ZDW fluctuation along the fiber length, the parametric gain is considered to be obtained from a multi-section nonlinear fiber arrangement (L. Provino et.al, 2003). Each section has different value of ZDW. The ZDW fluctuation is considered to vary continuously (M. Farahmand et.al, 2004). The evolution of signal and idler amplitudes can be described by integrating the propagation matrix in which dispersion fluctuation is taken into account.

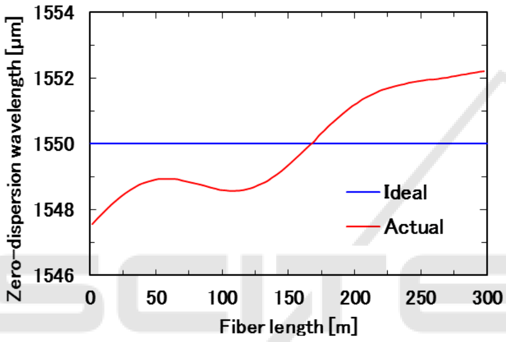

Figure 3: Example of a ZDW fluctuation map numerically recorded along the fiber length.

As an example, a ZDW fluctuation map numerically recorded along the fiber length is shown in Fig. 3 (A. Mussot, 2006). The blue line represents the ideal ZDW in a uniform fiber but the red line indicates its actual fluctuation. Assuming that the fiber mentioned in section 2 is subjected to this ZDW fluctuation, its FOPA gain performance is investigated with different values of γ.

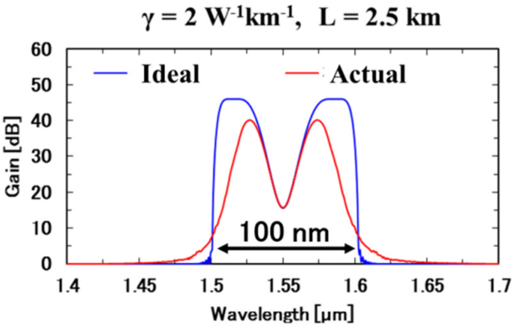

Figure 4: FOPA signal gain spectra with the effect of ZDW fluctuation in Fig. 3 when γ=2 W^{-1}km^{-1} and L =2.5 km.

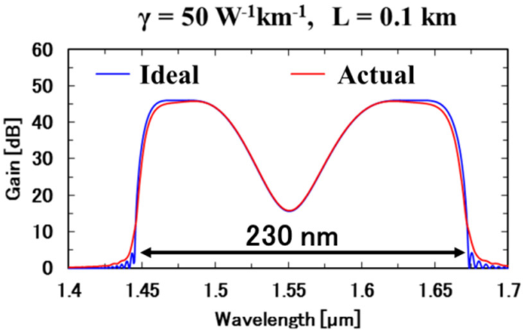

Figure 5: FOPA signal gain spectra with the effect of ZDW fluctuation in Fig. 3 when γ=20 W^{-1}km^{-1} and L =0.1 km.

Figure 4 shows calculated FOPA signal gain spectra which are related to γ =2 W^{-1}km^{-1} and L =2.5 km. When γ becomes 25 times larger, calculated FOPA signal gain spectra in Fig. 5 show that only a 0.1-km-long fiber is required to obtained similar values of signal gain. In Figs. 4 and 5, the blue lines (ideal) represent the ideal FOPA performance in a perfectly uniform fiber and the red lines (actual) show the gain performance with the effect of ZDW fluctuation. As can be seen, the actual FOPA performance in Fig. 4 is very different from the ideal performance due to the effect of ZDW fluctuation. But that difference is almost suppressed as shown in Fig. 5. Moreover, the spectral bandwidth is broadened from 100 to 230 nm. Those features show that the influence of the ZDW fluctuation on FOPA performance can be reduced and the amplification band of FOPA can be extended by using optical fibers with high nonlinearity and short length.

3.2 Highly Nonlinear Tellurite Microstructured Optical Fibers

Based on the idea in section 3.1, a highly nonlinear tellurite microstructured optical fiber was designed and fabricated. The fiber was made by using our developed tellurite glass 78TeO$_2$–5ZnO-12Li$_2$O-5Bi$_2$O$_3$ (TZLB) mol%. The cross-sectional image of the fiber was taken by a scanning electron microscope (SEM) and is shown in Fig. 6. The calculated nonlinear coefficient was γ=676 W^{-1}km^{-1}. This value is about 23 times larger than that of a highly nonlinear silica fiber (M. Hirano et.al, 2016).

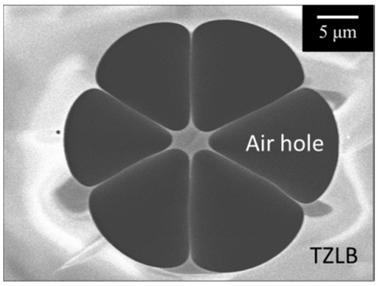

Figure 6: SEM cross-sectional image of the fabricated tellurite MOF.

The outer-diameter fluctuation along a 1-m-long section of the fabricated tellurite MOF is shown in Fig. 7. Compared with the expected value, the fluctuation is less than ±0.53 %. The corresponding ZDW fluctuation which was calculated by a commercial full-vectorial mode solver (Lumerical-Mode Solution software) based on the finite element method and the perfectly matched layer boundary condition is shown in Fig. 8. The ZDW varies in the range of 1557 ±2 nm. FOPA gain performance regard to this ZDW fluctuation was calculated and shown in Fig. 9. The pump source is 5 W at 1557 nm. As can be seen, FOPA signal gain spectra spanned from approximately 1430 to 1710 nm (280-nm bandwidth) and could be maintained although ZDW fluctuation occurred.

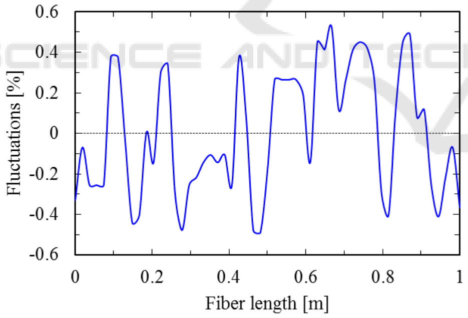

Figure 7: Evolution of the fiber outer-diameter along a 1-m-long section of the fabricated tellurite MOF.

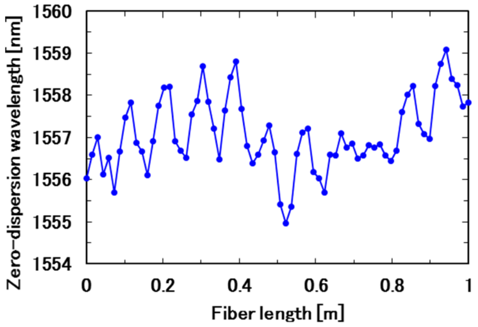

Figure 8: Evolution of the calculated ZDW along a 1-m-long section of the fabricated tellurite MOF in Fig. 7.

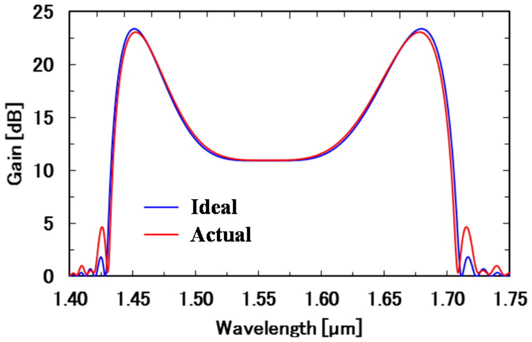

Figure 9: Calculated FOPA signal gain spectra when the ZDW fluctuation in Fig. 8 is taken into account.

4 CONCLUSIONS

For the first time, our simulations show that the degradation of FOPA signal gain performance which is caused by the fiber transverse geometry variation can be suppressed by using highly nonlinear optical fibers with short fiber length. Compared to silica fibers, highly nonlinear tellurite MOFs with high nonlinear coefficient and short fiber length are expected to make FOPA performance more practical by extending its amplification bands and maintaining its signal gain spectra even in presence of fiber transverse geometry variation.

ACKNOWLEDGEMENTS

This work was supported by the JSPS KAKENHI Grant Number 15H02250 and by JSPS KAKENHI Grant Number 17K14671.

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