Optical Parametric Gain of Tellutire/Phosphate Highly Nonlinear Optical Fiber

Edmund Samuel, Tong Hoang Tuan, Koji Asano,Takenobu Suzuki and Yasutake Ohishi
Research Center for Advanced Photon Technology, Toyota Technological Institute,
2-12-1 Hisakata Tempaku, Nagoya 468-8511, Japan

Keywords: Optical Parametric Amplifier, Microstructured Optical Fiber, Chromatic Dispersion.

Abstract: We optimized the optical pump power to realize better phase-matching, higher parametric amplification gain and broader bandwidth for highly nonlinear optical fibers with tailored chromatic dispersions. The core-clad materials have large refractive index difference of 0.49. The gain bandwidth calculated are 108 and 104 nm for the step index and hybrid micorstructured optical fibers with two zero dispersion wavelengths respectively. The broadest bandwidth in our calculation is 108 nm for step index fiber at pump wavelength 1238 nm.

1 INTRODUCTION

The need of modern and future communication system of multi-terabit transmission in optical communication is to be ultrafast capability with wider bandwidth. The demand of highly nonlinear optical fibers is increasing in optical signal processing for applications such as wavelength division multiplexing and optical time division multiplexing systems. These highly nonlinear optical fibers appear to be promising solutions and superior as they are passive, low cost and robust optical processors. In addition to these features the fiber optical parametric amplifiers (FOPAs) are spectrally flexible and operational with low noise (Djordjevic, 2011); (Nugent et al., 2009).

The optical parametric amplifier (OPA) through four wave mixing (FWM) can deliver amplified signal gain at arbitrary wavelengths to compensate the fiber loss (Droques et al., 2011); (Djordjevic, 2011); (Lavoute et al., 2010); (Mussot et al., 2006); (Vedadi et al., 2006); (Parolari et al., 2005). In optical communication system with wavelength division multiplexers needs to equalize optical power levels of the various channels which can be achieved by such OPA with highly nonlinear optical fibers. Moreover, fiber OPA has great potential applications such as signal generation, broadband wavelength conversion, optical sampling and optical switching.

Recently much attention has been given to non-silica high index and high nonlinear materials such as tellurite, fluoride and chalcogenide (Zhang et al., 2012); (Stepien et al., 2010); (Gao et al., 2013); (Souza et al., 2006). Moreover, these materials have excellent optical transparency in comparison to silica which has the transmission window limited to less than 3 µm. The tellurite glasses have generated broad interest due to excellent properties such as corrosion resistance, lowest phonon energy among oxides, high linear and nonlinear refractive indices, single mode guidance, dispersion control and good glass stability.

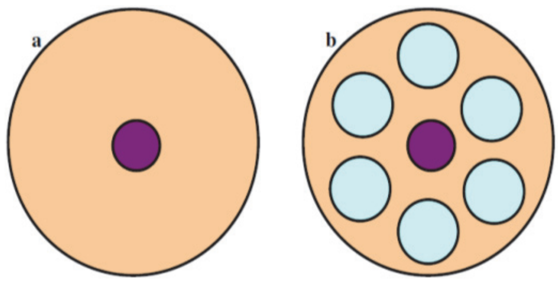

Figure 1: The schematic design of highly nonlinear tellurite/phosphate (a) Step Index fiber and (b) microstructured optical fiber.

Tong et al., has successfully demonstrated the tellurite-glass core and phosphate cladding fiber (Tuan et al., 2012). This core-clad combination provides much better flexibility to tailor chromatic

Samuel E., Hoang Tuan T., Asano K., Suzuki T. and Ohishi Y..
Optical Parametric Gain of Tellutire/Phosphate Highly Nonlinear Optical Fiber.
DOI: 10.5220/0004610704070411
In *Proceedings of the 4th International Conference on Data Communication Networking, 10th International Conference on e-Business and 4th International Conference on Optical Communication Systems* (OPTICS-2013), pages 407-411
ISBN: 978-989-8565-72-3

dispersion, because the core and clad materials have large refractive index difference of 0.49. It was observed that by changing tellurite core diameter of fiber from 0.8 to 6.0 µm, the zero dispersion wavelength changes from 1150 to 1850 nm. However, the nonlinear properties especially FOPA performance of the tellurite/phosphate optical fiber has not yet been clarified. Hence, the tellurite/phosphate hybrid microstructured optical fiber (HMOF) as shown in Fig. 1 was used for our simulation work in this paper.

2 PARAMETRIC GAIN THEORY

The refractive indices (n) as a function of wavelength for tellurite and phosphate glasses are given by the Sellmeier dispersion equation (Ghosh and Yajima, 1998).

$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - L_i^2} \tag{1}$$

where λ is the wavelength in µm and the Sellmeier fitting coefficients A_i and L_i (Tuan et al., 2012). They are tabulated in Table 1.

Table 1: Sellmeier fitting coefficients for tellurite and phosphate.

Material	Tellurite		Phosphate	
	***A*i**	***L*i**	***A*i**	***L*i**
i=1	1.6719	0.0216	1.24285	0.100699
i=2	1.3482	0.2391	0.23711	6.99996
i=3	0.62186	6.8356	9.96689	999.9990

Optical parametric amplifiers have attracted immense interest due to their ability of providing uniform gain bandwidth with low noise figure. In addition to this smaller length fiber and low peak power required for FWM process to be occurred. Moreover, the single pump OPA has broad parametric gain bandwidths. The net parametric gain (G) in fiber optical parametric amplification is given by Eq. (2) (Agrawal, 2000a); (Chaudhari et al., 2012).

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

where, g is the gain coefficient given by Eq. (3), γ is nonlinear coefficient, L is the fiber length and P is pump power.

$$g = \left[(\gamma P)^2 - \frac{1}{4}(\Delta\beta + 2\gamma P)^2\right]^{1/2} \tag{3}$$

The gain coefficient includes phase-match Δβ which is given by Eq. (4). Phase-matching is a key factor for parametric amplification and it has been calculated analytically to realize the efficient parametric gain (Agrawal, 2000a); (Yaman et al., 2005).

$$\Delta\beta = 2\sum_{m=1}^{\infty} \frac{\beta_{2m}}{(2m)!}(\omega_s - \omega_p)^{2m} \tag{4}$$

where, β_{2m} are dispersion parameter coefficients, ω_p and ω_s are pump and signal frequency, respectively.

When β_2 becomes very small, higher order dispersion parameters must be considered at wavelengths close to ZDW. Therefore, phase-matching condition (Agrawal, 2000b) is expressed as follows

$$\beta_2\Omega^2 + \frac{1}{12}\beta_4\Omega^4 + 2\gamma P = 0 \tag{5}$$

where β_2 and β_4 are the second and fourth order derivative of the propagation, $\Omega = \omega_s - \omega_p$ is the shift in frequency between signal and pump frequency.

3 RESULTS AND DISCUSSION

Figure 2(a) shows the calculated parametric gain for a step index fiber with core diameter of 0.944 µm and a chromatic dispersion with two ZDW at 1223 and 1252 nm. The parametric gain was obtained for the different pump-wavelength λp. It has been observed from Fig. 2(b) that there is symmetrical decrease in bandwidth on both side of the pump wavelength (λp=1238 nm). This is due to the dependence of parametric gain on chromatic dispersion and dispersion parameters which are also symmetrical in nature. Here, the parametric gains at each ZDW are similar and much flatter in comparison to parametric gain observed for different pump wavelengths. When λp=1238 nm, the gain bandwidth of step index fiber is 108 nm.

Figure 2(b) shows the view of parametric gain which was calculated using the chromatic dispersion as shown in Fig. 2(a). The broader and brighter shade between 1223 and1252 nm clearly reveals the presence of peak parametric gain and broad bandwidth between two ZDWs and the peak value of the parametric gain is 33 dB. However, the bandwidth changes with pump wavelengths as shown in Fig. 2(b). This is because β_2 moves from the normal to anomalous regime and returns to normal regime again.

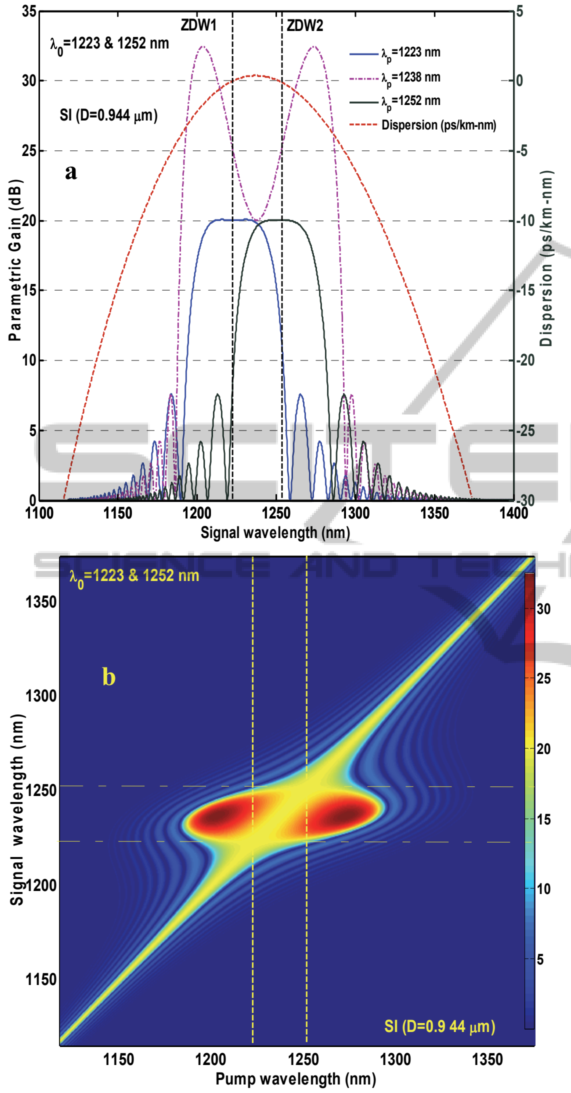

Figure 2: (a) Parametric gain for two ZDW step index fiber with P=100mW and L=1m, (b) Parametric gain spectra view for wide range of pump and signal wavelength.

Figure 3(a) and (b) show the parametric gain variation with signal and pump wavelengths for HMOF whose chromatic dispersion is shown in Fig. 3(a). It was assumed that the peak power P=100 mW, fiber length L=1 m, core diameter of HMOF D=0.9 μm, air hole diameter d=1μm and pitch p=1.4 μm. When λp=1255 nm, the gain bandwidth of HMOF is 104 nm and the maximum peak gain of 29 dB can be obtained. However, we can see that the parametric gain spectrum and bandwidth mainly depends on pump wavelength. The parametric gain reduces to 20 dB with a narrow bandwidth (64 and 63 nm) at each ZDW (1241 and 1269 nm), but significantly has flatter bandwidth at each ZDW.

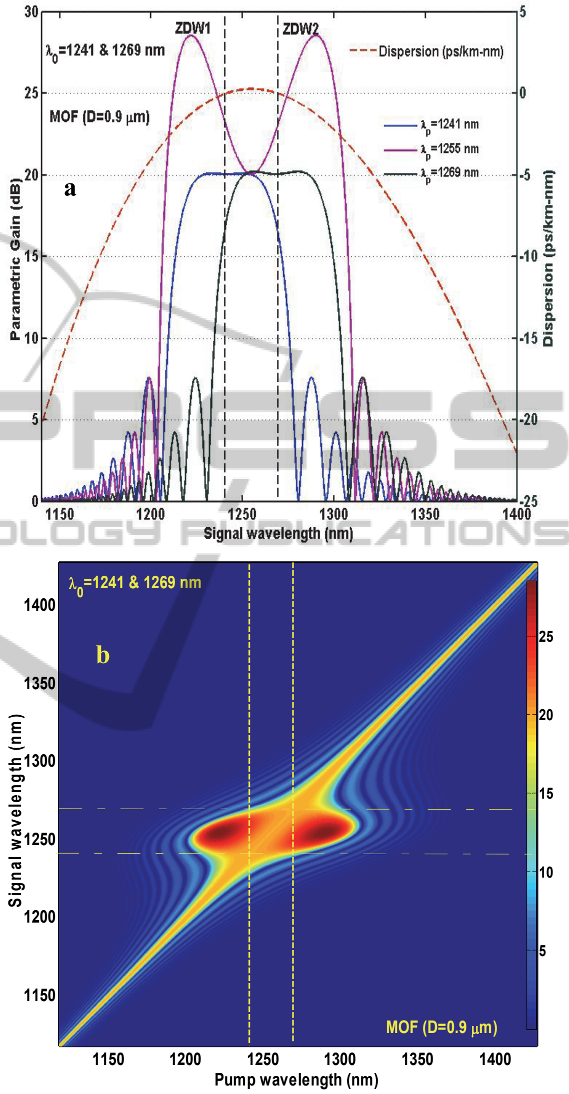

Figure 3: (a) Parametric gain for two ZDW MOF with P=100mW and L=1m, (b) Parametric gain spectra view for wide range of pump and signal wavelength.

The phase-matching diagrams for the step index fiber and HMOF with γP changed from 10000 to 40000 m^{-1} were calculated. The phase-matching conditions were calculated using Eq. (5). The phase-matching is very significant obligation in order to achieve efficient parametric amplification. Figure 4(a) shows the phase-matching curves for the two ZDW step index fiber. This shows that signal wavelengths are much closer to pump wavelengths between the first and second ZDW (1223 and 1252 nm). Their variation in this region reveals the effect of nonlinear coefficient and peak power significantly. When γP increases from 10000 to 40000 m^{-1} the signal and idler wavelengths shift away from each other. The phase-matching curves observed for HMOF with two ZDW is as shown in Fig. 4(b). In Fig. 4(b) the similar phase-matching curves were observed between the first and second ZDW (1241 and 1269 nm) for different γP values.

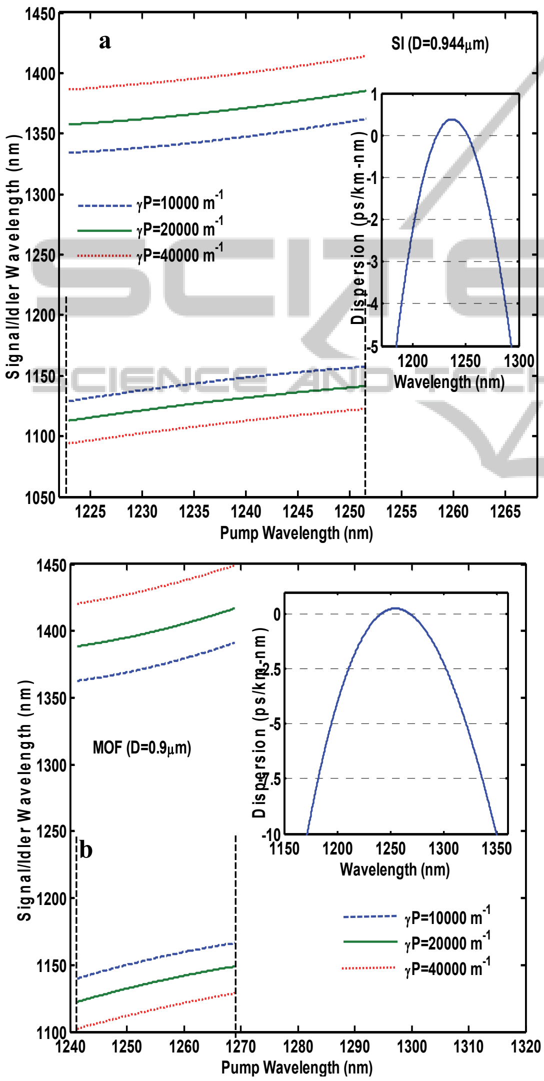

Figure 4: Phase-matching curves for (a) Step Index fiber and (b) Hybrid microstructured optical fiber.

4 CONCLUSIONS

The HMOF has the bandwidth of 104 nm and it has been shown that for the given set of nonlinearity coefficient and peak power a parametric gain 33 dB for step index fiber and 29 dB for HMOF can be obtained. While, the phase-matching curves for the step index and HMOF with two ZDW were observed to be between their respective ZDWs. It is concluded that for broad bandwidth it is very much necessary to have very small values of β_2 and β_4 simultaneously.

ACKNOWLEDGEMENTS

This research was by the Ministry of Education, Culture, Sports, Science and Technology under the support Program for Forming Strategic Research Infrastructure (2011-2015).

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