Double-pumped FOPA with 40 dB flat gain over 81 nm bandwidth

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Abstract *We report the construction and characterization of a record performance continuous-wave double-pumped fiber-optical parametric amplifier exhibiting 40 dB flat gain over 81nm bandwidth.*

Introduction

Optical amplifiers are key elements in many types of optical systems including optical fiber communication links and laser-based radars. An interesting alternative to the mature Erbium-doped fiber amplifier (EDFA) is the fiber optic parametric amplifier (FOPA) [1]. FOPAs have a gain spectrum that is essentially “man-made” in the sense that it is governed mainly by geometric parameters that are under direct control by the design and fabrication of the fiber and for this reason they offer the possibility of high gain broadband devices [2]. The double-pumped version of the FOPA (2P-FOPA) can exhibit, in an ideal fiber, flat gain over hundreds of nanometers just by tuning the pump wavelengths nearly symmetrically around the zero dispersion wavelength of the fiber (λ_0). Some fiber properties will impose a limit on the ultimate available flat bandwidth: fourth order dispersion (β_4), random longitudinal variations of λ_0, and random birefringence can introduce a non-negligible amount of phase mismatch that will depend on the signal wavelength thus introducing a distortion in the gain spectrum and limiting the bandwidth. However, as we show in this paper, the substantial progresses in the fabrication of highly nonlinear fibers (HNLFs) [3] facilitates the construction of wideband 2P-FOPAs. We achieved 40 dB flat gain over 81 nm bandwidth and show that the bandwidth was not limited by intrinsic fiber properties but by the availability of pumps symmetrically located around λ_0. Our results can be compared to the 40 dB over 50 nm best CW performance previously reported [4].

Experimental setup

The experimental setup is shown in Fig. 1. Tunable lasers at λ_1 and λ_2 were used as pumps sources. In order to avoid stimulated Brillouin scattering, the pump lasers were phase modulated using a combination of four sinusoidal RF signals [1]. The EDFAs provide high power in the C and L bands. Optical band-pass filters (BPFs) were used to reject most of the ASE from the EDFAs. Polarization controllers (PCs) were used to adjust the states of polarization of pumps and the signal so as to maximize the parametric gain. The spectrum was measured using an optical spectrum analyzer (OSA) with 0.1 nm resolution. Two HNLFs (A and B) were used to implement the 2P-FOPA. The fiber A has L = 250 m, $A_{\mathrm{eff}} = 10.1\mu\mathrm{m}^2$, $S_0 = 0.026$ ps/nm^2-km, $\langle\lambda_0\rangle$ = 1571.7 nm, $\beta_4 = 7\times10^{-5}$ ps^4/km, estimated variation of λ_0 of 3 nm, and a measured differential group delay (DGD) of 0.024 ps. The fiber B has L = 350 m, $A_{\mathrm{eff}} = 9.4\mu\mathrm{m}^2$, $S_0 = 0.025$ ps/nm^2-km, $\langle\lambda_0\rangle$ = 1561.9 nm, $\beta_4 = 2.5\times10^{-5}$ ps^4/km, estimated variation of λ_0 of 0.5 nm, and DGD = 0.031 ps. The values of $\langle\lambda_0\rangle$, β_4, and the fluctuation of λ_0 were measured using the noise injection method reported in [5].

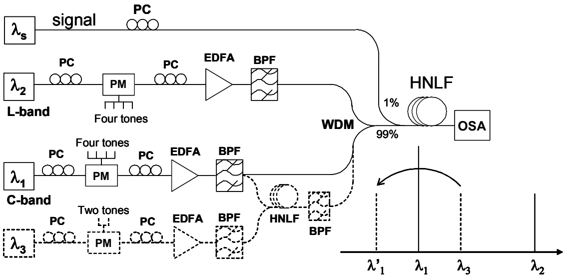

Fig. 1. Experimental setup. High power pumps are generated with EDFAs at λ_1 and λ_2 directly, or via wavelength conversion at λ'_1 by coupling a high power pump and signal at λ_1 and λ_3 into another HNLF.

Using EDFAs to generate high power pumps will limit the pump separation to around 70 nm. To achieve larger separations one can construct a single-pumped FOPA that is optimized to provide very high conversion efficiency in a spectral band not covered by EDFAs. We implemented this kind of wavelength converter (see the dashed lines in Fig. 1) by pumping a 50 m HNLF with 5 W. We obtained up to 1.4 W of converted power at wavelengths between 1490 to 1530 nm. After filtering we could obtain 1 W pump power at λ'_1 within the 2P-FOPA HNLF.

Results

HNLF A was used with a pump separation of 70 nm. The pumps were at λ_1 = 1535.3 nm and λ_2 = 1605.3 nm, while the pump powers were P_1 = 1 W and P_2 = 0.5 W. The pump wavelengths were optimized to produce a flat gain spectrum which is shown in Fig. 2 with circles. On-off flat gain ($G \cong 30 \pm 1.5$ dB) was obtained over 50nm bandwidth. The continuous line is calculated by numerically solving the nonlinear Schrödinger Equation (NLSE), incorporating the experimental parameters. The only fitting parameters were λ_0 = 1571.2 nm, an effective interaction length of L_{int} = 215 m, and nonlinear coefficient $\gamma = 13$ W^{-1}/km. The fitting parameter L_{int} takes into account the parametric gain reduction due to the fact that the pumps and signal polarizations are not co-polarized (maximum gain) along the whole propagation. L_{int} also accounts for gain reduction due to longitudinal

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variations of λ_0. The agreement with experimental data is very good. The dashed and dotted line curves show the simulations for $\beta_4 = 0$ and $\beta_4 = 7\times10^{-5}$ ps^4/km respectively, with the pump frequencies located symmetrically around ω_0. In these cases the available bandwidth in the region between the pumps is identical with the optimized case, indicating that β_4 is not dictating the shape in that region and consequently is not limiting the bandwidth. The structure of the sidelobes is very sensitive to changes in β_4 and pump detuning however.

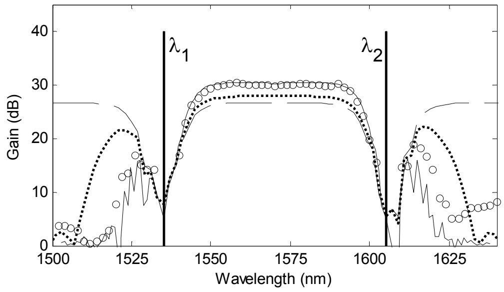

Fig. 2. Calculated and measured (circles) gain spectra for HNLF A. Dashed and dotted lines: calculated spectra with no pump detuning for $\beta_4 = 0$ and $\beta_4 = 7\times10^{-5}$ ps^4/km respectively.

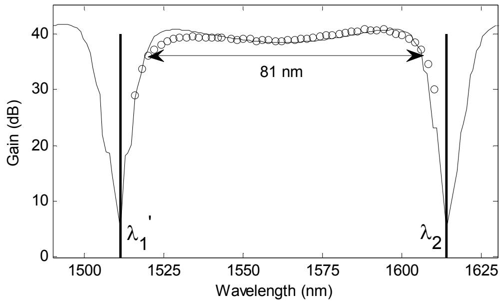

Fig. 3. Calculated and measured (circles) gain spectra for HNLF B. A 3-dB bandwidth of 81 nm was measured.

HNLF B was tested with the maximum pump separation in our setup (103 nm). The pump powers were P_1 = 1 W and P_2 = 1.1 W. We characterized the gain spectrum by locating one pump at λ_2 = 1613.85 nm while the other pump was tuned between 1510.5 and 1511.5 nm (i.e. the tuning range where flat gain could be observed). The circles in Figure 3 show the flattest experimental gain spectrum, which was obtained for λ'_1 = 1511.29 nm. The 3-dB bandwidth was measured between 1523.9 and 1604.9 nm. There is a 1.5-dB tilt due to Raman gain produced by pump at λ'_1. Even though the measured Raman gain at λ_2 was 2.5 dB, the strong asymmetry produced between the pumps (5 dB at the output) did not lead to a noticeable ripple. The solid line in Fig. 3 shows the NLSE simulation using λ_0 = 1562.3 nm, L_{int} = 215 m, and γ = 14 W^{-1}/km as fitting parameters. The agreement is very good indicating that gain distortions arising from fluctuations of λ_0 and polarization misalignment due to random birefringence are not considerable for this pump separation. To further investigate the characteristics of the 2P-FOPA, the pump was tuned in order to find the tuning range where flat gain was possible: from λ'_1 = 1511.5 to 1510.5 nm the gain progressively increased by 5 dB while the ripple increased by 1 dB, and this was in close agreement with simulations. We stress that in our setup the pump separation bandwidth was limited by the wavelength separation between the L-band pump and the λ_0 of the HNLF. Since the HNLF B has a low value of β_4 and reduced fluctuations of λ_0, it can be expected that a larger bandwidth could be obtained simply by increasing the pump separation. The calculated gain spectra in figure 4 show that HNLF B can potentially provide a flat gain spectrum even for a pump separation of 180 nm, with a 3-dB bandwidth of almost 170 nm. The dotted line represents the case when the pump center of gravity coincides with λ_0, while the solid line represents the optimum condition. Both an increase in β_4 and in pump separation increases the sensitivity to pump detuning. With negative values of β_4 it is even more difficult to achieve wideband operation. Therefore, fibers with low and positive β_4 are the best candidates to implement very broadband 2P-FOPAs.

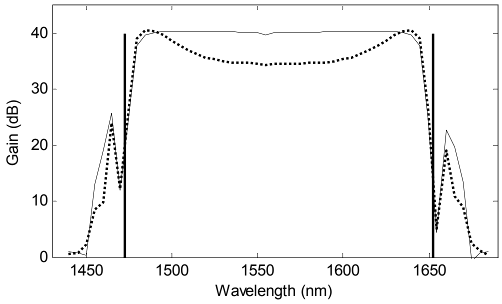

Fig. 4. Calculated spectra using parameters of HNLF B for a pump separation of 180 nm with (solid line) and without (dashed line) pump detuning.

Conclusions

In this paper we have described the performance of a double-pumped fiber-optical parametric amplifier exhibiting 40 dB flat gain over 81nm bandwidth. The bandwidth was not limited by fiber properties, but by pump wavelengths relative to λ_0 of the HNLF.

Acknowledgment

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