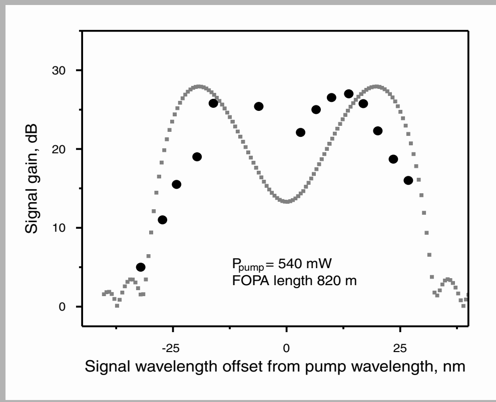
Laser Phys. Lett. **2**, No. 4 , 190–193 (2005) / **DOI** 10.1002/lapl.200410162

Abstract: Development of broadband fiber optical parametric amplifier based on highly nonlinear fiber pumped with tunable continuous wave fiber laser is reported. Creation of highly nonlinear fiber with optimized parameters is presented. Over 50 nm bandwidth continuous wave optical parametric gain in highly nonlinear fiber has been measured.



Signal gain in 820 m of HNLF pumped with 540 mW of CW fiber laser

Continuous-wave broadband fiber optical parametric amplifier based on 150 m of HNLF pumped with fiber laser

M.A. Solodyankin, [1,*] *A.N. Guryanov,* [2] *N.A. Kazantseva,* [1] *V.F. Khopin,* [2] *M.M. Bubnov,* [1] *M.E. Likhachev,* [1] *and E.M. Dianov* [1]

[1] Fiber Optical Research Center at the General Physics Institute of the RAS, 38 Vavilov Str., Moscow 119991, Russia
[2] Institute of Chemistry of High Purity Substances of the RAS, 49 Tropinin Str., Nizhny Novgorod 60360, Russia

Received: 3 November 2004, Revised: 10 November 2004, Accepted: 12 November 2004
Published online: 23 November 2004

Key words: parametric fiber amplifier; HNLF

PACS: 42.65.Yj

1. Introduction

The bandwidth of fiber optical parametric amplification (FOPA) is not restricted by an optical phonon spectrum in comparison with a Raman amplifier. Moreover, parametrical amplification does not depend on stimulated emission on particular transition. Thus, there are no principle limitations to achieve extremely wide spectral bandwidth of FOPA in any wavelength region. To increase width of spectral band of FOPA, we should optimize such parameters as pump power, fiber nonlinearity, fiber dispersion properties and uniformity of fiber characteristics with fiber length.

The principal ability to create an optical amplifier with wider bandwidth then one provided by existing Er-doped fiber amplifiers (EDFA) and Raman amplifiers makes FOPA attractive for application in telecommunication area. Therefore, many research groups have started investigation of FOPA operating around 1.5 μm spectral regions. In pulsed mode pumping, authors of reference [1] have received 200 nm bandwidth fiber OPA. But operation in pulsed mode makes such FOPA impractical for most telecommunications applications. Continuous wave (CW) optical fiber parametric amplifier with bandwidth of 75 nm [2] has been reported with use of 2.9 km of dispersion shifted fiber (DSF).

* Corresponding author: e-mail: solod@fo.gpi.ru

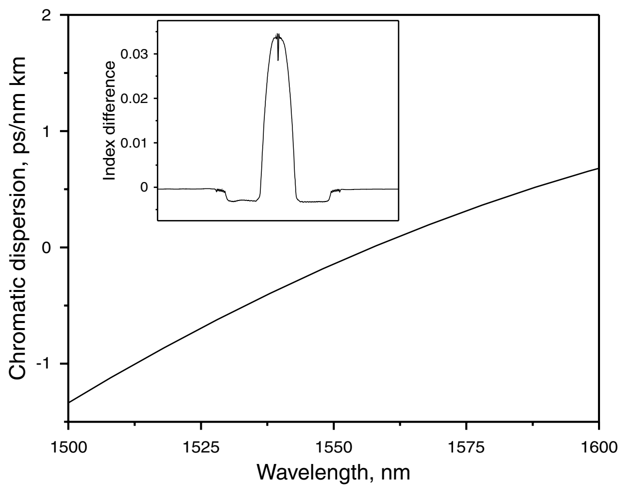


Figure 1 Chromatic Dispersion of HNLF. Insertion represents index profile

Use of highly nonlinear fiber (HNLF) as a parametric gain medium gives an opportunity to decrease required pump power or fiber length dramatically. Recently, several researches have published results of parametrical amplification in HNLF with CW pump [3,4]. They have reported gain bandwidth across a range of 46 nm (at 10 dB gain level) in three sequentially combined different pieces of HNLF of total length of 500 m [4]. Radiation of laser diode amplified by a multi-stages Erbium-doped amplifier was used as a pump. To prevent Brillouin backscattering, authors of [1,3,4] references had to use a phase modulator for widening of a spectrum line of a semiconductor pump source. Disadvantages of the scheme are its complexity and necessity of a mandatory interstage filtering of amplified spontaneous emission (ASE). To eliminate these disadvantages, we have used an Er-doped fiber laser as a pump in our research. In opposite to other authors who used HNLF of third-party, we have had facilities to produce fiber by ourselves. Due to this, we have been able to control fiber characteristics and select optimal parameters for FOPA.

Here, we demonstrate CW wideband parametric gain in a specially designed HNLF pumped with a fiber laser.

2. Highly nonlinear fiber design

Taking into account current characteristics for fiber telecommunication amplifiers, we have targeted to meet specific requirements for the FOPA being developed, such as high gain (15–20 dB), wide amplification spectral band (exceeding typical values for EDFA 35–40 nm), and simplicity.

To be applicable in telecommunication sphere, fiber for parametric amplification should have cut-off wavelength less than 1500 nm (in order to be a single-mode) and zero dispersion wavelength (ZDW) around pump wavelength. It imposes a limitation on difference of index Δn between core and cladding. In case of employing silica fiber with highly Germanium-doped core, the maximal difference of index is 3.6%, thus, leading to fiber nonlinearity restriction.

FOPA spectral bandwidth mainly depends on phase-matching, pump wavelength offset from ZDW and combination of fiber length and product of γP_{pump}, where γ is a nonlinearity coefficient; P_{pump} is a pump power [5]. Phase matching exceptionally is a function of dispersion of a fiber. Fiber chromatic dispersion depends on a shape of the index profile and the core diameter. In fiber designing, it is difficult to obtain the small dispersion slope less than +0.02 ps/km/nm^2 at the ZDW around the 1.55 μm band with realizing the large Δn. At the same time, the control of the ZDW of the fiber becomes difficult. This requires quite precise tuning of the fiber parameters in comparison with the conventional single-mode fiber (SMF) or dispersion shifted fiber (DSF). Fluctuation of the core diameter with 0.5% results in the ZDW shift of about 30 nm of HNLF with a Δn of 3%. In our case, a root-mean-square variation of fiber diameter is 0.2 μm. Furthermore, the ZDW must be stabilized in the longitudinal direction in order to get long effective length in the HNLF.

On the basis of [6] we have made a mathematical model of a parametrical amplifier pumped around ZDW in order to better understand dependence of FOPA characteristics on fiber and pump parameters. We have optimized the fiber profile to obtain wide spectral phase-matching simultaneously with the highest possible nonlinearity coefficient. The way of optimization is described below. First, we took a shape of index of profile and found a maximum possible level of Δn for cut-wavelength less than 1500 nm and ZDW around 1550. Then, we built dispersion curves for different fiber diameter (with 0.05 μm pitch of a diameter), calculated phase matching for every curve, and simulated theoretical parametric gain. We traced and fixed a dependence of phase-matching width and shape of gain spectrum on a fiber diameter. Finally, we selected a shape of fiber profile where at a constant pump level the widest gain spectrum was obtained and diameter variation had a least influence on a shape of gain spectrum. Based on the chosen shape of fiber profile, a fiber preform was made by MCVD (modified chemical vapor deposition).

A fiber samples with a number of diameter have been drawn in order to get a required ZDW. Chromatic dispersion of the fiber we used for parametrical amplification has been measured by interference technique [7]. The chromatic dispersion curve and the fiber profile are shown in Fig. 1. The HNLF has effective area 10.5 μm^2 and Δn 0.035. Nonlinear refractive index n_2 of fiber is 3.1×10^{-16} cm^2/W according to formula for n_2 calculation that was given in [8]. Thus, nonlinearity coefficient γ of HNLF is 12 W^{-1} km^{-1}. The HNLF dispersion slope around ZDW is +0.0197 ps/km/nm^2.

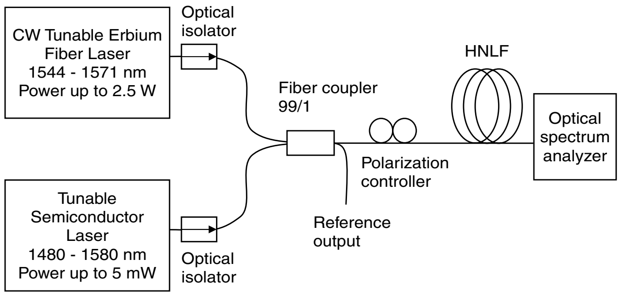


Figure 2 Experimental setup

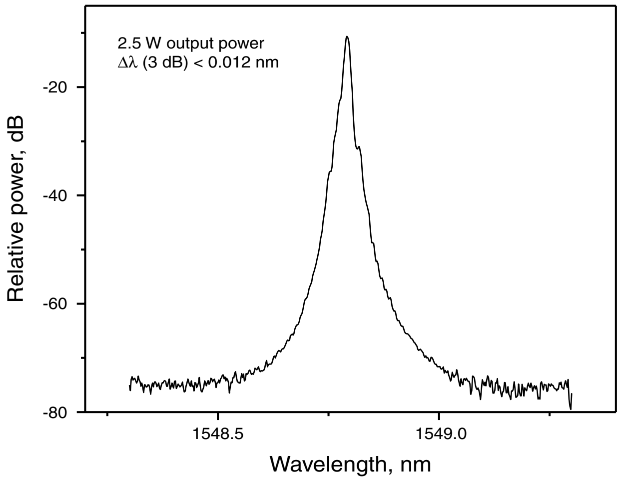


Figure 3 Typical emission spectrum of the CW tunable erbium fiber laser

3. Experimental setup

The setup is shown in Fig. 2. An external cavity tunable semiconductor laser serves as a signal source. It has a tuning spectral range from 1480 nm to 1580 nm and provides power up to 5 mW. The FOPA pump is a continuous wave tunable Erbium fiber laser with 2.5 W maximum output power. We have designed it specially for pumping FOPA. Fine tunability in 1544–1571 nm spectral range gives us flexibility to pump different tested fiber samples around zero dispersion wavelengths, as it needs to be pumped close enough to ZDW in order to obtain an appreciable parametric gain. We have managed to achieve spectral bandwidth of the CW tunable Erbium laser $\Delta\lambda$ less than 0.012 nm at a half power level (Fig. 3), what is approximately 1.5 GHz. Significant Brilluoin backscattering (SBS) with such bandwidth of a pump source has not been observed during our experiments. We have measured SBS suppression more than 23 dB. Signal to noise ratio of Erbium fiber laser is more than 60 dB. Thus additional pump source filtering is not required.

The signal and pump are combined by means of a fiber coupler and launched into the OPA medium. The output signal is monitored by an optical spectrum analyzer (OSA). The polarization of the signal is adjusted with a polarization controller (PC) to yield the maximum gain. The value of gain has been defined as a difference of signal power level inside the HNLF at the beginning and at the end of fiber.

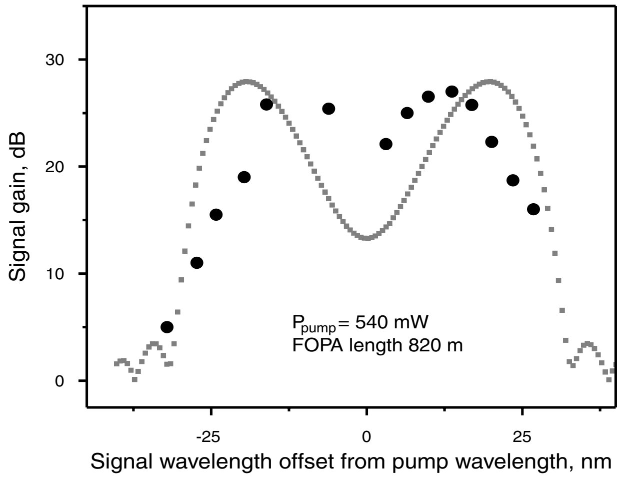


Figure 4 Signal gain in 820 m of HNLF pumped with 540 mW of CW fiber laser. Black circles correspond to measured data; gray squares are simulated gain

Using the setup mentioned above, parametric gain of several highly nonlinear fibers has been measured in order to create a broadband FOPA.

4. Experimental results

Fig. 4 shows parametrical amplification achieved in 820 m length HNLF pumped with 540 mW at 1553.9 nm. Black circles represent measured gain. Gray squire shows simulated signal gain. The maximal signal amplification is 27 dB; gain bandwidth at 15 dB level exceeds 50 nm. As it can be seen, simulated gain wider than measured one. In our opinion, this mismatch is caused by longitudinal chromatic dispersion variation.

Length of HNLF has been shortened to enlarge phase-matching spectral band by means of reducing impact of ZDW longitudinal variation. Thus, we had to increase pump power in order to keep amplification value over 10 dB. 150 m of the HNLF and 1.3 W pump power has been used in this case. As measurements have been performed over a wavelength range of tunability of our signal source, right part of measured parametric gain, which is shown in Fig. 5 by black circles, goes only up to 1580 nm. Consequently, experimentally measured gain bandwidth is 45 nm. Parametric gain is symmetric of pump wavelength due to property of four-wave mixing. Moreover, symmetrical idler wavelength generation has been observed in right part of gain spectrum. Taking it in to account, theoretically

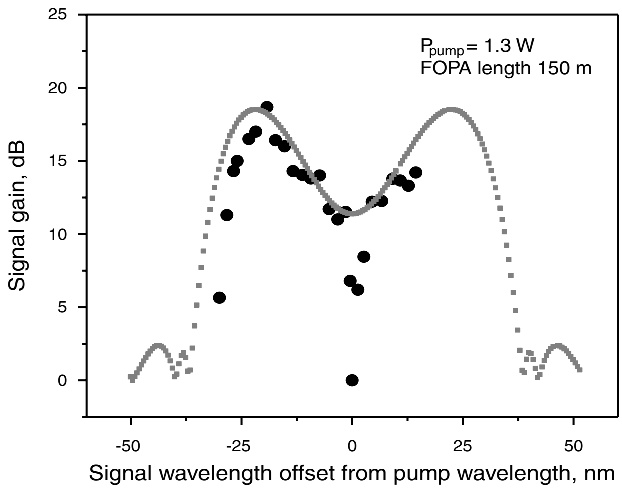


Figure 5 Signal gain in FOPA 150 m length pumped with 1.3 W of CW fiber laser. Black circles correspond to measured data; gray squares are simulated gain

extended total parametric gain bandwidth in 150 m of the HNLF is over 60 nm width at 10 dB level.

Gray squares in Fig. 5 show simulated gain. Experimental result is in a good agreement with our OPA model. The difference between simulated gain and experimentally measured gain at zero offset exists because our FOPA model does not consider pump and signal sources bandwidth. Simulated gain has mathematical simple discontinuity when signal wavelength is exactly the same as pump wavelength. The model defines the mean of gain function at zero point to be continuous and smooth. Therefore it does not have a gap around zero offset signal wavelength from pump wavelength. True parametric gain spectrum of a signal has a gap when signal wavelength is close to pump wavelength due to nonzero bandwidth of pump and signal sources. This is why experimentally measured gain has a typical break at zero offset.

Indeed, comparing gain bandwidth in 820 m and 150 m fiber pieces, it can be concluded that bandwidth of the similar FOPAs can be enlarged if shorter pieces of HNLF are used and pump power is increased.

5. Resume

Thus, we have developed and investigated a CW broadband all-fiber optical parametric amplifier. The proposed FOPA configuration is based on HNLF with CW fiber laser pump. HNLF with optimal parameters has been designed. We have received gain in excess of 10 dB over 50 nm bandwidth in 820 m of HNLF and theoretically extended gain over 60 nm with use of just 150 m length HNLF and continuous-wave pump, delivered by CW fiber laser.

Our results indicate that optical parametric amplifiers gain bandwidth can be enlarged with use of shorter length of HNLF and higher pump power.

The suggested approach can be applied to the fabrication of the broadband all-fiber optical parametric amplifiers for future optical telecommunication systems.

Acknowledgements Authors would gratefully like to acknowledge U.G. Akchmetshin for help in fiber designing and A.K. Senatorov for chromatic dispersion measurements.

References

[1] M. Ho, K. Uesaka, M. Marhic, et al., J. Lightwave Tech. **19**, 977–981 (2001).

[2] S.E. French and J.L. Blows, Continuous wave optical fibre parametric amplifier with flattened gain, in: Optical Amplifiers and Their Applications (Optical Society of America, Washington DC, 2001), paper PD7 (July 1–3, Stresa, Italy).

[3] S. Radic, C.J. McKinstrie, A.R. Chraplyvy, et al., New Class of Continuous Wave Parametric Amplifiers, in: The Optical Fiber Communication Conference and Exhibit, 17–22 March, 2002, Anaheim, CA, USA, FB5-1.

[4] J. Hansryd and P. Andrekson, IEEE Photon. Tech. Lett. **13**, 194–196 (2001).

[5] R.H. Stolen and J.E. Bjorkholm, IEEE J. Quantum Electron. **18**, 1062–1071 (1982).

[6] C. Floridia, M.L. Sundheimer, L. de S. Menezes, and A.S.L. Gomes, Opt. Commun. **223**, 381–388 (2003).

[7] A. Belov, E. Dianov, and A. Kurkov, Quantum Electron. **13**, 1680–1682 (1986).

[8] A. Boskovic, S.V. Chernikov, and J.R. Taylor, Opt. Lett. **21**, 1966–1968 (1996).