**Dieses Dokument ist eine Zweitveröffentlichung (Verlagsversion) /
This is a self-archiving document (published version):**

Tobias Baselt, Christopher Taudt, Bryan Nelsen, Andrés Fabián Lasagni, Peter Hartmann

**Experimental study of supercontinuum generation in an amplifier
based on an Yb³⁺ doped nonlinear photonic crystal fiber**

Erstveröffentlichung in / First published in:

SPIE LASE. San Francisco, 2016. Bellingham: SPIE, Vol. 9731 [*Zugriff am: 22.05.2019*]. DOI:
<https://doi.org/10.1117/12.2213212>

Diese Version ist verfügbar / This version is available on:

<https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-350941>

„Dieser Beitrag ist mit Zustimmung des Rechteinhabers aufgrund einer (DFGgeförderten) Allianz- bzw. Nationallizenz frei zugänglich.“

This publication is openly accessible with the permission of the copyright owner. The permission is granted within a nationwide license, supported by the German Research Foundation (abbr. in German DFG).
www.nationallizenzen.de/

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Experimental study of supercontinuum generation in an amplifier based on an Yb³⁺ doped nonlinear photonic crystal fiber

Tobias Baselt, Christopher Taudt, Bryan Nelsen, Andrés Fabián Lasagni, Peter Hartmann

Tobias Baselt, Christopher Taudt, Bryan Nelsen, Andrés Fabián Lasagni, Peter Hartmann, "Experimental study of supercontinuum generation in an amplifier based on an Yb³⁺ doped nonlinear photonic crystal fiber," Proc. SPIE 9731, Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XV, 97310L (4 March 2016); doi: 10.1117/12.2213212

SPIE.

Event: SPIE LASE, 2016, San Francisco, California, United States

Experimental study of supercontinuum generation in an amplifier based on an Yb³⁺ doped nonlinear photonic crystal fiber

Tobias Baselt^{*abc}, Christopher Taudt^{acd}, Bryan Nelsen^b, Andrés Fabián Lasagni^{ac}, Peter Hartmann^{ab}

^aFraunhofer-Institut für Werkstoff- und Strahltechnik IWS, 01277 Dresden, Germany; ^bUniversity of Applied Sciences Zwickau, Institute of Leupold-Institute for Applied Natural Sciences / Optical Technologies, D-08056 Zwickau; ^cTechnische Universität Dresden, Institute of Manufacturing Technology, George-Bähr-Straße 3c, 01069 Dresden, Germany; ^dTechnische Universität Dresden, Medizinische Fakultät Carl Gustav Carus, George-Bähr-Straße 3c, 01069 Dresden, Germany

ABSTRACT

The use of supercontinuum light sources in different optical measurement methods, like microscopy or optical coherence tomography, has increased significantly compared to classical wideband light sources. The development of various optical measurement techniques benefits from the high brightness and bandwidth, as well as the spatial coherence of these sources. For some applications, only a portion of the broad spectral range can be used. Therefore, an increase of the spectral power density in limited spectral regions would provide a clear advantage over spectral filtering. This study describes a method to increase the spectral power density of supercontinuum sources by amplifying the excitation wavelength inside a nonlinear photonic crystal fiber (PCF). An ytterbium doped photonic crystal fiber was manufactured by a nanopowder process (drawn by the company fiberware) and used in a fiber amplifier setup as the nonlinear fiber medium. In order to characterize the fiber's optimum operational characteristics, group-velocity dispersion (GVD) measurements were performed on the fiber during the amplification process. For this purpose, a notch-pass mirror was used to launch the radiation of a stabilized laser diode at 976 nm into the fiber sample for pumping. The performance of the fiber was compared with a conventional PCF. Finally, the system as a whole was characterized in reference to common solid state-laser-based photonic supercontinuum light sources. An improvement of the power density up to 7.2 times was observed between 1100 nm to 1380 nm wavelengths.

Keywords: supercontinuum, ytterbium doped photonic crystal fiber, light source, nanosecond pulses

1. INTRODUCTION

New technologies in the field of optical metrology, microscopy and optical coherence tomography expand the requirements for high power white light sources [1, 2]. The power spectral density, spatial coherence, spectral width, spectral distribution and stability are the most important parameter for many applications in the field of optical metrology [3]. A light distribution with a high spectral width, spectral power density and spatial coherence is hereinafter referred to here as supercontinuum (SC) [4]. Coherent octave-spanning SC can be generated in photonic crystal fibers (PCFs) by launching short pulses with a wavelength located near the zero-dispersion wavelength of the PCF into the fiber [5]. Fiber based supercontinuum light sources currently allow the highest power densities with single mode fiber output (spectral power density over 1 mW/nm [6]) and have become indispensable in many areas of optical technologies and instrumentation like optical coherence tomography [7]. Enhancement of the bandwidth of supercontinuum generated in microstructured fibers has been demonstrated with different techniques [8, 9, 10]. For most applications, only a small part of the entire spectrum can be utilized [11].

* tobias.baselt@fh-zwickau.de; phone +49 375 536 1970; Fax +49 375 536 1503
www.fh-zwickau.de

Techniques for spectral filtering which simultaneously enables an increase in the power spectral density, offer a clear advantage compared to conventional spectral filtering techniques. Furthermore, the damage threshold value limits the maximum pulse energy which can be coupled into the PCF [12]. Amplifying the input signal inside a doped PCF can be an approach to solving the problem. Master Oscillator Power Amplifier (MOPA) fiber systems are a convenient way to amplify a seed signal [13]. It is known that Ytterbium doped fiber amplifiers enable amplification in a wide spectral range between 1000 nm and 1150 nm [14]. These doped optical fibers could be fabricated in the past using a state-of-the-art production method called modified chemical vapor deposition (MCVD) with an excellent degree of purity [15]. If the purity of the core material is not of central importance, also a nanopowder method can be utilized permitting a great geometric flexibility in the fiber design [16]. Ytterbium-doped aluminum co-doped silica glass fibers produced by these sol-gel or nanopowder technique show tunable emission from 1033 nm to 1108 nm [17]. In addition, these techniques have been also successfully employed in the production of microstructured fibers [18]. Information about the group-velocity dispersion (GVD) is important to evaluate the non-linear properties of the fiber. To determine the dispersion in doped fibers under optical pumping, the well suited time-frequency-domain dispersion measurement method [19] was combined with a pump laser setup.

In this study, a method to increase the spectral power density of supercontinuum sources by amplifying the excitation wavelength inside a nonlinear photonic crystal fiber is demonstrated. The ytterbium doped photonic crystal fiber manufactured by a nanopowder process was used in a fiber amplifier setup as the nonlinear fiber medium. The fiber's optimum operational characteristics are determined during the amplification process. Finally, the performance of the fiber is compared with a conventional PCF.

2. EXPERIMENTAL ARRANGEMENT AND SETUP

The fiber amplifier described here consists of an ytterbium doped photonic crystal fiber. A fiber preform design, realized by a nanopowder process (drawn by the company fiberware) was applied. The fiber was core pumped by a single mode diode laser (BL976-PAG700 / THORLABS) at 976 nm and pump power of up to 735 mW. The microchip seed laser (1064-Q / Impex-hightech) has a peak power of 11 kW at a pulse length of 2.1 ns and a repetition rate of 12.5 kHz.

The pump was free space coupled in the Yb^{3+} doped PCF by a notch mirror (980 nm, OD4 Notch Filter, Edmund Optics) (Fig. 1a). The spectral power densities were carried out using two calibrated spectrometers (AvaSpec-ULS3648 and AvaSpec-NIR256-1.7 from Avantes). The fibers were calibrated immediately before the measurement by means of a reference light source.

In order to characterize the guiding properties and the zero-dispersion wavelength (λ_0) of the optical fiber during operation, the group delay is measured. The used time-frequency domain interferometer set up for the group delay measurements is shown in Fig. 1b.

The light of a fiber-coupled supercontinuum light source, developed and manufactured in cooperation with fiberware GmbH, is fed into the Mach-Zehnder interferometer. The supercontinuum light source is pumped by a microchip laser which produces ns-pulses at a wavelength of 1064 nm. The interferometric setup has an implemented controllable delay line to investigate the time delay of the probe in order to find the equalization wavelength [20]. A micro positioning unit MT1/M-Z8 (from Thorlabs) which possesses a spatial resolution of 0.5 μm was used, allowing time resolutions on femtosecond timescales. A laser diode was launched at an angle of 20° into the test fiber by a notch filter which is used as a dichroic mirror (980 nm, OD4 Notch Filter, Edmund Optics) and operates stabilized at 976 nm with up to 700 mW of optical power. The poor transmission of the notch mirror in the wavelength range below 700 nm requires a power readjustment of the reference branch during measurement. Measurements both with and without pump laser radiation are possible in this setup.

The doping concentration of Yb^{3+} was determined by the manufacturing process. The overall concentration in the doped core was 0.5 mol/% Yb_2O_3 and 2 mol/% Al_2O_3 . Segregations in the doped core area and a technology-related symmetrical inhomogeneous material distribution were observed (Fig. 2a). To characterize the structural parameters, high resolution images of the fiber were taken using a scanning electron microscope as shown in Fig. 2b. The most relevant geometrical parameter of the fiber are listed in Table 1.

After the drawing process no segregations or symmetrical inhomogeneous material distribution were observed.

Figure 2: a) Atomic number contrast at point EDX 1 SiO_2 , EDX 2 $\text{SiO}_2 + \text{Al}_2\text{O}_3$ and EDX 3 $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Yb}_2\text{O}_3$. b) Scanning electron microscope image recording of the microstructured fiber geometry Yb^{3+} doped PCF.

3. RESULTS AND DISCUSSION

To evaluate the setup described before, the group-velocity dispersion of the Yb^{3+} doped PCF endlessly was investigated. The group delay of the fiber was measured with and without pump radiation at 976 nm wavelength. The laser radiation during the measurement leads only to a very small shift of the group delay (see Fig. 3). The wavelength dependence is flat around 1 μm and it did not alter the dispersion coefficient around 1060 nm. A shift of zero-dispersion wavelength between both measurements was not observed. The detected zero-dispersion wavelength of 1030 ± 3 nm was close to the seed laser wavelength of 1064 nm. The investigated group delay $\tau(\lambda)$ in Fig. 3 was fitted using the Sellmeier polynomial ($R^2 = 0.998$). Also the calculated GVD is shown. The Sellmeier coefficients are $A_1 = 3.74 \cdot 10^7 \pm 2.3 \cdot 10^6$, $A_2 = -71.7 \pm 0.7$ and $A_3 = 4 \cdot 10^{-5} \pm 4 \cdot 10^{-7}$.

Figure 3. Measured group delay $\tau(\lambda)$ of the investigated fiber in the fundamental mode with and without pump radiation and b) the corresponding calculated GVD.

The spectral power density was measured for different levels of pump power (up to 735 mW). The Yb^{3+} doping of the fiber leads to high absorption without pumping between 900 nm to 1000 nm and only poor spectral power density in the visible spectrum (below $0.1 \mu\text{W}/\text{nm}$) as shown in Fig. 4. The spectral power density in the near infrared (1030 nm to 1370 nm) without pumping, is comparable to similar PCFs without Yb^{3+} doping and appropriate seed pulse parameter [21]. The nanopowder technology and the occurring high OH contamination leads to a strong absorption at 1385 nm [18].

Figure 4: Power spectral density of the generated supercontinuum as function of the pumping power at 976 nm wavelength.

The results reported here demonstrate that the fiber offers the possibility to increase the spectral power density in the near infrared region. Between 1100 nm to 1370 nm, the power spectral density increases by pumping at 976 nm by a factor of up to 7.2 (at 1365 nm) and averaged 4.3 times. In the wavelength region between 1100 nm to 1370 nm, the shape of the spectrum can be significantly flattened from 7.8 dB variation without pumping to 2.9 dB variation at maximum pump power.

4. CONCLUSIONS

This report demonstrates the possibility to increase the spectral power density of supercontinuum sources by amplifying the excitation wavelength inside Yb^{3+} doped nonlinear photonic crystal fiber. A conventional microchip seed laser was coupled to a photonic crystal fiber and wide supercontinuum spectra were generated. The photonic crystal fiber used for this purpose was characterized. The fiber was core pumped by a single mode diode laser at 976 nm and the pump power was varied from 0 up to 735 mW. An increase in power spectral density of up to 7.2x and a 4.9 dB flattening of the spectral distribution in the wavelength range from 1100 nm to 1370 nm was observed.

ACKNOWLEDGMENTS

The authors want to thank the Federal Ministry of Education and Research for financial support under grant number FKZ 03FH004PX3 as well as the members of the optical technologies working group at the West Saxon University of Applied Sciences Zwickau, the company fiberware and Prof. Lasagni at the Institute of Manufacturing Technology (Technische Universität Dresden) for fruitful discussions.

REFERENCES

- [1] Dupont, S., Petersen, C., Thøgersen, J., Agger, C., Bang, O., Keiding, S. R.: "IR microscopy utilizing intense supercontinuum light source," *OPTICS EXPRESS* 20, Bd. No. 5, 4887 (2012)
- [2] Heisea, B., Schausbergera, S. E., Häuserb, S., Plankc, B., Salabergerc, D., Leiss-Holzingerd, E., Stiftera, D.: "Full-field optical coherence microscopy with a sub-nanosecond supercontinuum light source for material research," *Optical Fiber Technology* (2012)
- [3] R. Leitgeb, C. K. Hitzenberger, and A. F. Fercher: "Performance of fourier domain vs. time domain optical coherence tomography" *OPTICS EXPRESS* 11, 889 (2003)
- [4] J. M. Dudley, J. R. Taylor: "Supercontinuum Generation in Optical Fibers" Cambridge University Press, (2008)
- [5] R. Holzwarth, T. Udem, T. W. Hansch, J. C. Knight, W. J. Wadsworth, and P. S. J. Russell, "Optical frequency synthesizer for precision spectroscopy," *Phys. Rev. Lett.* 85, 2264–2267 (2000).
- [6] T. Schreiber, J. Limpert, H. Zellmer, A. Tünnermann, K.P. Hansenb.: "High average power supercontinuum generation in photonic crystal fibers" *Optics Communications* 228, 71–78, (2003)
- [7] Y. Hattori, H. Kawagoe, Y. Ando, M. Yamanaka and N. Nishizawa: "High-speed ultrahigh-resolution spectral domain optical coherence tomography using high-power supercontinuum at 0.8 μ m wavelength" *Applied Physics Express* 8, 082501 (2015)
- [8] J. Picot-Clementea, C. Strutynskia, F. Amrania, F. Désévédaya, J-C Julesa, G. Gadreta, D. Dengb, T. Chengb, K. Nagasakab, Y. Ohishib, B. Kiblera, F. Smektalaa: "Enhanced supercontinuum generation in tapered tellurite suspended core fiber" *Optics Communications* 354, 374–379 (2015)
- [9] G. Genty, M. Lehtonen, H. Ludvigsen, and M. Kaivola: "Enhanced bandwidth of supercontinuum generated in microstructured fibers" *Optics Express* 12, 3471–3480 (2004)
- [10] J. Nathan Kutz, C. Lyngå, and B. J. Eggleton: "Enhanced Supercontinuum Generation through Dispersion-Management" *Optics Express* 13, 3989–3998 (2005)
- [11] A. Unterhuber, B. Považay, K. Bizheva, B. Hermann, H. Sattmann, A. Stingl, T. Le, M. Seefeld, R. Menzel, M. Preusser: "Advances in broad bandwidth light sources for ultrahigh resolution optical coherence tomography" *Physics in Medicine and Biology*, 49, NO. 7 (2004)
- [12] T. Baselt, T. Hammer, F. Basan and P. Hartmann: "Application of a microchip laser-pumped photonic crystal fiber supercontinuum source for high-sensitive cavity ring down optical loss measurements" *Proc. SPIE* 7195, 71951T (2009)
- [13] C. Jauregui, T. Eidam, J. Limpert, and A. Tünnermann, "The impact of modal interference on the beam quality of high-power fiber amplifiers," *Opt. Express* 19, 3258–3271 (2011)
- [14] Pask, H.M., Carman, R.J., Hanna, D.C., Tropper, A.C., Mackechnie, C.J., Barber, P.R. and Dawes, J.M.: "Ytterbium-doped silica fibre lasers: versatile sources for the 1–1.2 μ m region," *IEEE Journal of Selected Topics in Quantum Electronics* Volume 1, NO. 1 (1995)
- [15] Andrew S. Webb, Alexander J. Boyland, Robert J. Standish, Seongwoo Yoo, Jayanta K. Sahu, David N. Payne: "MCVD in-situ solution doping process for the fabrication of complex design large core rare-earth doped fibers" *Journal of Non-Crystalline Solids* 356, 848–851 (2010)
- [16] I. Kasik, O. Podrazky, J. Mrazek, J. Cajzl, J. Aubrecht, J. Probstova, P. Peterka, P. Honzato and A. Dhar: "Erbium and Al₂O₃ nanocrystals-doped silica optical fibers" *Technical Sciences*, 62, 641–646 (2014)
- [17] Urs Pedrazza, Valerio Romano, Willy Lüthya: "Yb³⁺:Al³⁺:sol-gel silica glass fiber laser" *Optical Materials* 29, 905–907 (2007)
- [18] A. Baz, H. El Hamzaoui, I. Fsaifes, G. Bouwmans, M. Bouazaoui and L. Bigot: "A pure silica ytterbium-doped sol-gel-based fiber laser" *Laser Physics Letters* 10, 055106 (5pp) (2013)

- [19] Baselt, T., Taudt, Ch. and Hartmann, P. "Time-frequency-domain dispersion measurement in rare earth doped large effective mode area multicore fibers" Proc. SPIE 8961, 89612Z 7 (2014)
- [20] T. Baselt, Ch. Taudt, A.-F. Lasagni, P. Hartmann (2015): "Experimental measurement of group velocity dispersion during operation in cladding-pumped large-mode-area Yb-doped fibers" SPIE.OPTICAL METROLOGY 9525,142 (2015)
- [21] T. Baselt, Ch. Taudt, and P. Hartmann: "High power fiber amplifier with adjustable repetition rate for use in all-fiber supercontinuum light sources" Proc. SPIE 8961, 89613F (2014)