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Erstveröffentlichung in / First published in:

SPIE LASE. San Francisco, 2017. Bellingham: SPIE, Vol. 10088 [*Zugriff am: 22.05.2019*].

DOI: <https://doi.org/10.1117/12.2252259>

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SPIE.

Event: SPIE LASE, 2017, San Francisco, California, United States

All-fiber supercontinuum source with flat, high power spectral density in the range between 1.1 μm to 1.4 μm based on an Yb³⁺ doped nonlinear photonic crystal fiber

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ABSTRACT

Supercontinuum light sources provide a high power spectral density with a high spatial coherence. Coherent octave-spanning supercontinuum can be generated in photonic crystal fibers (PCFs) by launching short pulses into the fiber. In the field of optical metrology, these light sources are very interesting. For most applications, only a small part of the entire spectrum can be utilized. In biological tissue scattering, absorption and fluorescence limits the usable spectral range. 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 all-fiber-based setup enables higher output power and power stability. An ytterbium-doped photonic crystal fiber was manufactured by a nanopowder process (drawn by the fiberware GmbH, Germany) 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. The performance of the fiber-based setup was compared with a free space setup. Finally, the system as a whole was characterized in reference to common solid state-laser-based supercontinuum light sources. An improvement of the power density was observed in the spectral range between 1100 nm to 1400 nm.

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

1. INTRODUCTION

The power spectral density, spatial coherence, spectral width, spectral distribution and stability are the most important parameter for high power white light sources in the field of optical metrology [1, 2, 3]. One light source which meets all these requirements is a PCF based supercontinuum (SC) light source [4]. Coherent octave-spanning SC can be generated in photonic PCFs by launching short laser pulses with a wavelength located near the zero-dispersion wavelength of the PCF into the fiber [5]. These light sources currently allow the highest power densities with single mode fiber output [6]. A spectral power density over 30 mW/nm based on an all fiber laser setup was shown [7]. This high performance method provides better parameters for many areas of optical metrology and biophotonics using techniques like optical coherence tomography [8]. Enhancement of the bandwidth of pulsed-laser-based supercontinuum generated in microstructured fibers has been demonstrated with different techniques [9, 10, 11]. For some applications, only a small part of the entire spectrum can be utilized [12].

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There are different techniques to limit the output spectrally. All of these techniques result in a reduction of the spectral power density in the selected spectral range. In order to increase the spectral power density after filtering, the pulse peak power has to be increased. The damage threshold value limits the maximum pulse energy which can be coupled into the PCF [13]. The development of a method for spectral filtering with a simultaneous increase in the spectral power density would provide a clear advantage. Amplifying the input signal within a doped PCF offers the possibility to achieve it [14]. Master Oscillator Power Amplifier (MOPA) fiber systems can be used to amplify an optical signal [15]. Ytterbium doped fiber amplifiers enable amplification in a wide spectral range between 1000 nm and 1150 nm and absorb radiation between 850 nm to 1000 nm [16].

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 [17]. For a setup with a short fiber length, also a nanopowder method can be utilized permitting a great geometric flexibility in the fiber design [18]. In addition, these techniques have been also successfully employed in the production of microstructured fibers [19]. We show that the use of these fibers in an amplifier setup increase the spectral power density of supercontinuum sources by amplifying the excitation wavelength [14]. 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 setup on the optical table is compared with an all-fiber setup.

2. EXPERIMENTAL ARRANGEMENT AND SETUP

The Yb³⁺ doped PCF is used to build up a fiber amplifier. 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 with a pump power of up to 248 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.

In the first setup, the pump was free space coupled in the Yb³⁺ doped PCF by a notch mirror (980 nm, OD4 Notch Filter, Edmund Optics) (Fig. 1a). In the second setup the pump was launched in an optical isolator and a spliced wavelength division multiplexer (WDM). The radiation of the microchip seed laser was launched through an isolator spliced to the WDM (Fig. 1b). A homemade mode field adapter was implemented on the output fiber of the WDM. The mode field adapter was realized by tapering a fiber [20]. The taper transition must be sufficiently gradual to minimize the losses at every point. To minimize the length of a taper, the angle should be as low as necessary to suppress the losses [21]. The taper was prepared by the splicer FSM-100P+ / Fujikura and the cleaver CT-101 / Fujikura. The tapered and cleaved output of the WDM was spliced to the investigate PCF. In order to obtain the microstructure of the Yb³⁺ doped PCF, an adapted splice program was developed.

The spectral power densities were carried out using two calibrated spectrometers (AvaSpec-ULS3648 and AvaSpec-NIR256-1.7 from Avantes). The spectrometers were calibrated immediately before the measurement by means of a reference light source.

Figure 1: a) Schematic of the optical setup of the Yb³⁺ doped nonlinear photonic crystal fiber based amplifier. The nonlinear fiber medium enables the generation of supercontinuum at different levels of pump diode power. The setup used for the supercontinuum generation. MCL - microchip laser, LD – pump laser diode ($\lambda = 976$ nm), M - mirror, NM - notch mirror, AT - attenuator, PCF_{Yb} - Yb: doped PCF – fiber, LD - laser diode and Spec - spectrometer. b) Fiber based Setup with to OI - optical isolators, a WDM - wavelength division multiplexer and a MFA – mode field adapter.

The doping concentration of Yb³⁺ was determined by the manufacturing process. The overall concentration in the doped core was 0.5 mol/% Yb₂O₃ and 2 mol/% Al₂O₃. To characterize the structural parameters, high resolution images of the fiber were taken using a scanning electron microscope as shown in Fig. 2a.

Figure 2: a) Scanning electron microscope image recording of the microstructured fiber geometry Yb³⁺ doped PCF. b) Image of the splice between the Yb³⁺ doped PCF left and the tapered region of the WDM right.

The most relevant geometrical parameters of the fibers are listed in Table 1. The V parameter is calculated by the form in Eq. (1), the PCF fiber parameter V_{PCF} for photonic crystal fibers [22, 23].

$$V_{PCF}(\lambda) = \frac{2\pi}{\lambda} a_{eff}(\lambda) \sqrt{n_1^2(\lambda) - n_{2eff}^2(\lambda)} = \frac{2\pi a_{eff}(\lambda)}{\lambda} NA(\lambda) \quad (1)$$

The effective refractive index of the cladding, n_{eff} , and the effective core radius, a_{eff} , are highly dependent on the wavelength of the propagating radiation. At a wavelength of 1.06 μm the fiber is not operating in the single mode regime.

Table 1. Parameters of the constituent fiber.

Item	Yb3+ PCF
core diameter [μm]	4.8 ± 0.1
hole-to-hole distance [μm]	5.5 ± 0.1
capillary diameter [μm]	4.5 ± 0.1
V-parameter ($\lambda = 1.06 \mu\text{m}$)	5.8
zero-dispersion wavelength [nm]	1030 ± 3

3. RESULTS AND DISCUSSION

The spectral power density was measured for different levels of pump power (up to 248 mW). The pump power was limited by the WDM, which only handles power up to 300 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 using the appropriate seed pulse parameter [24]. The nanopowder technology and the high OH contamination leads to a strong absorption at 1385 nm

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

To get a gain in power spectral density the incoming light of the seed laser has to be amplified. The launched pump power shown in Fig. 4 is too low to get a massive gain in the desired spectral region. Compared to the free space setup, the integral power in the spectral range between 1100 nm to 1380 nm is 38% higher without pumping than the all fiber setup (Fig. 5). For the Amplification of the radiation in the shown spectral regenerative slope efficiency can be defined. The all-fiber setup shows in this case a sloop efficiency of 21 % higher than the sloop efficiency of the free space setup of 17 %. The shape of the spectrum is significantly flatter compared to similar build non-doped PCF [24].

Figure 5: Integral power in the spectral range between 1100 nm to 1380 nm with dependence of pump power for the free-space and all-fiber setup. The all-fiber setup shows a sloop efficiency of 21 % ($R = 0.988$) higher than the sloop efficiency of the free space setup of 17 % ($R = 0.997$).

For the seed laser and pump laser radiation, the splice loss on the PCF and the tapered single mode step index fiber was lower than the lurching loss in the free-space setup. The higher power leads to higher power spectral density between 1100 nm to 1380 nm. In the examined spectral range a flat broad optical continuum was generated. These results were obtained in an all-fiber setup with high mechanically stability.

4. CONCLUSIONS

The Yb^{3+} doped PCF is used to build up an all-fiber supercontinuum source for the spectral range between 1100 nm to 1380 nm. The all-fiber setup shows better power spectral density compared to the free-space setup. A significant increase of slope efficiency from 17% to 21 % for the all-fiber setup was demonstrated. Furthermore, the system reaches higher power spectral density in the second optical window (for analysis of biological tissue) when compared to sources based on non-doped PCF and similar seed laser conditions. 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 applied. The use of a high repetition rate fiber laser could improve the power spectral density by more than one order of magnitude.

5. ACKNOWLEDGMENTS

The authors want to thank the German 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 and the company fiberware.

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