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Development of a method to overcome the power threshold during supercontinuum generation based on an Yb-doped photonic crystal fiber

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Abstract. Optical coherence tomography benefits from the high brightness and bandwidth, as well as the spatial coherence of supercontinuum (SC) sources. The increase of spectral power density (SPD) over conventional light sources leads to shorter measuring times and higher resolutions. For some applications, only a portion of the broad spectral range can be used. Therefore, an increase of the SPD in specific limited spectral regions would provide a clear advantage over spectral filtering. This study describes a method to increase the SPD of SC sources by amplifying the excitation wavelength inside of a nonlinear photonic crystal fiber (PCF). An ytterbium-doped PCF was manufactured by a nanopowder process and used in a fiber amplifier setup as the nonlinear fiber medium. The performance of the fiber was compared with a conventional PCF that possesses comparable parameters. Finally, the system as a whole was characterized in reference to common solid-state laser-based photonic SC light sources. An order-of-magnitude improvement of the power density was observed between the wavelengths from 1100 to 1350 nm. [DOI: 10.1117/1.OE.57.2.021207]

Keywords: supercontinuum; ytterbium-doped photonic crystal fiber; light source; nanosecond pulses.

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1 Introduction

Light sources with higher spectral power density (SPD) enable the investigation of structures deep within biological tissue. Strong wavelength-dependent absorption limits the optical penetration depth in which biological tissue can be examined.[1] Nonetheless, in specific spectral regions, low absorption permits the examination of deeper tissue layers. These regions of significantly low absorption are referred to as optical windows.[2] Furthermore, wavelength-dependent scattering leads to considerable optical losses during the examination of biological tissue. Scattering and absorption define the penetration depth. In the second optical window (1100 to 1350 nm), the penetration depth reaches a maximum for various biological tissues.[3] Optical coherence tomography of biological specimens would benefit from the high SPD of supercontinuum (SC) light sources in the second optical window, which could enable an increase in sensitivity and imaging speeds.[4–7]

Coherent multioctave spanning SC is currently generated in photonic crystal fibers (PCFs) by launching short and intense laser pulses with a wavelength near the zero-dispersion wavelength of the PCF into the fiber core.[8–11] The maximum power output of SC sources based on PCFs is currently limited to about 30 mW/nm.[12–14] If an increase of the SC SPD in the second optical window is desired, the pulse peak power has to be increased. On the other hand, the damage threshold value of the PCF endface limits the maximum pulse energy, which can be launched into the PCF.[15] The input facet damage and absorption losses limit the SPD.[13] Amplifying the pulse within a doped PCF offers the possibility to achieve an increase of SPD.[16]

Since ytterbium-doped fiber amplifiers enable amplification in a wide spectral range between 1000 and 1150 nm,[17] an ytterbium-doped PCF manufactured by a nanopowder process was used in a fiber amplifier setup as the nonlinear fiber medium. We show that the use of these PCFs in an amplifier setup increases the SPD of SC sources by amplifying the excitation wavelength.[18]

2 Experimental Arrangement and Setup

The optical setup of the amplified PCF was based on a standard master oscillator power amplifier configuration. The SC generating Yb^{3+} doped PCF was also used as the gain medium in a fiber amplifier arrangement (Fig. 1).

The construction process for the unique fiber used for these experiments started with a fiber preform design that was realized by a nanopowder process and then drawn by the company fiberware, GmbH.[16] In the setup used to generate the SC, the Yb core was pumped by a linearly polarized single-mode diode laser at 976 nm. The passively Q-switched seed laser, operating at 1064 nm, had a pulse energy of 19.8 μJ, a pulse length of 2.1 ns, and a repetition rate of 12.5 kHz. The SPD measurements were carried out using two intensity-calibrated spectrometers.

A second set of experiments was designed to compare the effectiveness of the amplified PCF when contrasted against a similar passive PCF SC light source. In order to

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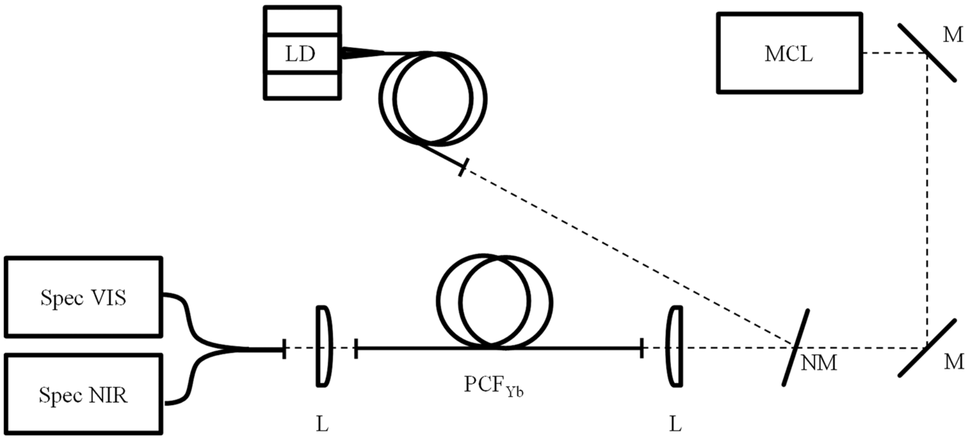

Fig. 1 Schematic of the optical setup of the Yb3+ doped nonlinear PCF-based amplifier. MCL, microchip laser; LD, pump laser diode ($\lambda = 976$ nm); M, mirror; NM, notch mirror; L, lens; PCF_{Yb}, Yb: doped PCF fiber.

characterize the guiding properties and the zero-dispersion wavelength of the Yb-doped PCF and compare it with a similar undoped optical fiber, the group delay is measured. The time–frequency domain interferometer setup for the group delay measurements is shown in Fig. 2.

The light from a fiber-coupled SC light source was analyzed using a Mach–Zehnder interferometer. The fiber under test is inserted into one path of the interferometer while the reference arm of the interferometer allows control over the delay in order to investigate the time delay and find the equalization wavelength.[19] A micro positioning translation stage possessing a spatial resolution of 1.5 μm was used to adjust the delay arm, achieving a group-delay time resolution of 9 fs.

The doping concentration of Yb3+ was determined by the manufacturing process. The overall concentration in

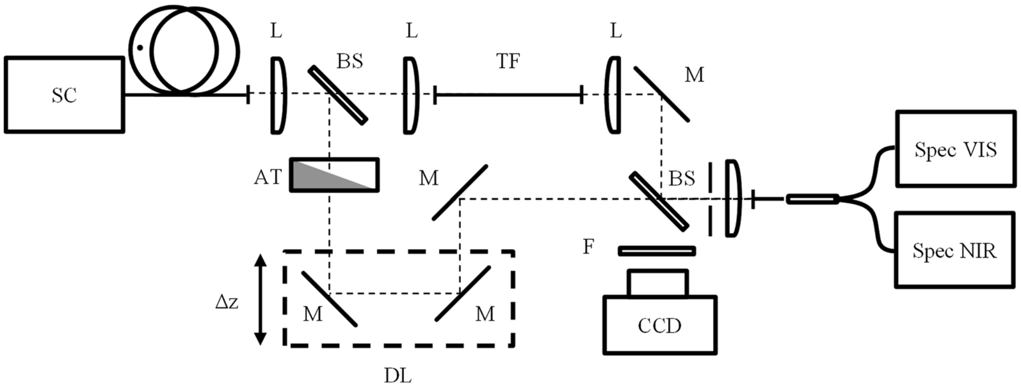

Fig. 2 Interferometric setup used for dispersion measurements. SC, supercontinuum light source; BS, nonpolarizing beam splitter; DL, delay line; M, mirror; TF, test fiber; AT, attenuator; F, bandpass filter; L, lens; CCD, camera; and Spec, spectrometer.

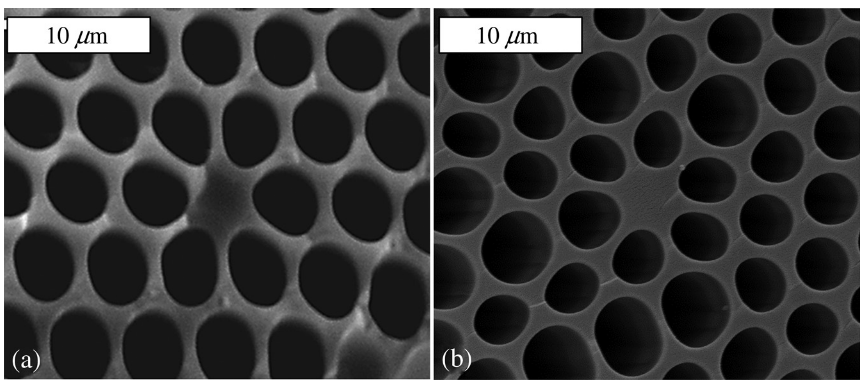

Fig. 3 Scanning electron microscope image of the microstructured fiber geometry: (a) Yb3+ doped PCF and (b) passive PCF.

Table 1 Parameters of the constituent fibers.

Item	Yb3+ doped PCF	Passive PCF
Core diameter (μm)	4.8 ± 0.1	4.5 ± 0.1
Hole-to-hole distance (μm)	5.5 ± 0.1	5.1 ± 0.1
Capillary diameter (μm)	4.5 ± 0.1	3.9 ± 0.5
V-parameter	5.8	5.2
Zero-dispersion wavelength (nm)	1030 ± 3	1018 ± 3

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.[16] High-resolution scanning electron microscope cross-sectional images of the fibers, shown in Fig. 3, were taken to characterize the structural parameters of the fibers.

After the drawing process, no segregations or symmetrical inhomogeneous material distributions were observed in the doped core [Fig. 3(a)]. The structures of the PCFs are measured based on the scanning electron microscope cross-sectional images. The geometrical parameters of the fibers are listed in Table 1.

3 Results and Discussion

To support the claim that the amplified PCF produces a greater SPD in the second optical window than its unamplified counterpart, a comparison between the above-mentioned doped and the undoped fiber was made. The group-velocity dispersion (GVD) is a critical factor in SC generation, and therefore, must be comparable for the two types of PCFs. In this work, the GVD was investigated by measuring the group delay, $\tau(\lambda)$, using the experimental configuration, as shown in Fig. 2. The group-delay data was fit with a three-term Sellmeier polynomial of the form:

$$\tau = \frac{a_1}{\lambda^2} + a_2 + a_3\lambda^2. \tag{1}$$

Figure 4 shows a side-by-side comparison of the two measured group delays for each fiber. The two curves are nearly identical in the region of zero dispersion.

The calculated GVD is shown in Fig. 5. The detected zero dispersion wavelengths of the undoped PCF (1011 ± 3 nm) and with Yb^{3+} doping (1016 ± 3 nm) are close to the seed laser wavelength of 1064 nm.

To determine the optimal seed pulse energy, the integral optical power in the visible range was measured. The seed pulse energy has to be lower than about 21 μJ to fall below the damage threshold (the effects of which can be seen in the inset of Fig. 6) of the examined bare PCF.

The slope efficiency in the second optical window was used as a practical measurement to determine the effectiveness of the SC generation. The slope efficiency in this optical window using the integral power between 1100 and 1350 nm was measured as a function of the pump power in Fig. 7. The slope efficiency was found to be 17%.

The evaluation of the results of the spectra generated in the undoped, doped unpumped, and doped pumped PCF is shown in Fig. 8. Between 1100 and 1350 nm, the

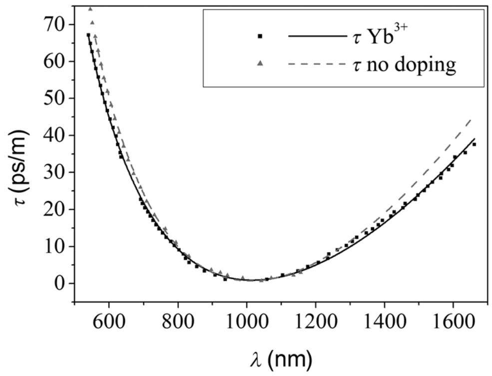

Fig. 4 Measured group delay, $\tau(\lambda)$, of the investigated fibers in the fundamental mode with and without Yb3+ doping in the core. The investigated group delay was fitted using the Sellmeier polynomial in Eq. (1).

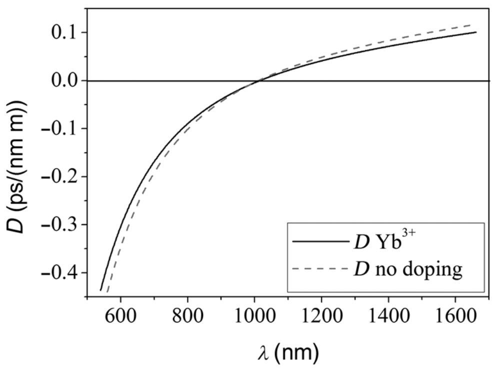

Fig. 5 Calculated GVD of the investigated fibers.

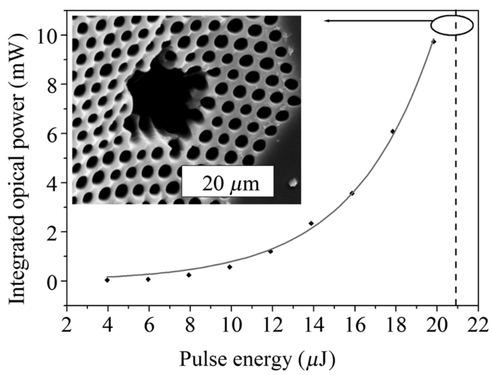

Fig. 6 Integral optical power in the visible range (380 to 780 nm) and seed pulse energy below the damage threshold of the bare PCF. The inset is an electron microscope image of the fiber cross-section after increasing the seed pulse energy above damage threshold.

SPD increases with core pumping by a factor of up to 7.2 at 1337 nm. In the second optical window, the power distribution of the spectrum has to be significantly flattened from a 7.8 dB variation without pumping to a 2.9 dB variation at maximum pump power. When these results are compared to a conventional SC light source with comparable seed laser parameters like the Koheras SuperK-Compact,[20] the doped PCF delivered an integral power in the second optical window that was more than eight times higher. An SC light source with a higher repetition rate could offer higher

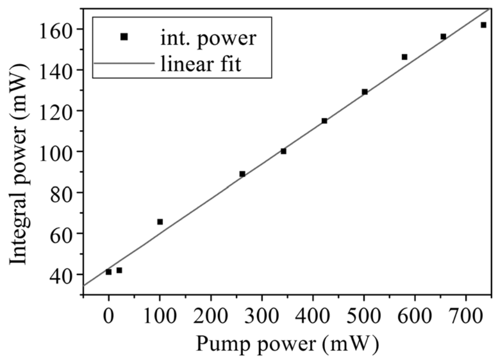

Fig. 7 Integral power from 1100 to 1350 nm in the second optical window as a function of pumping.

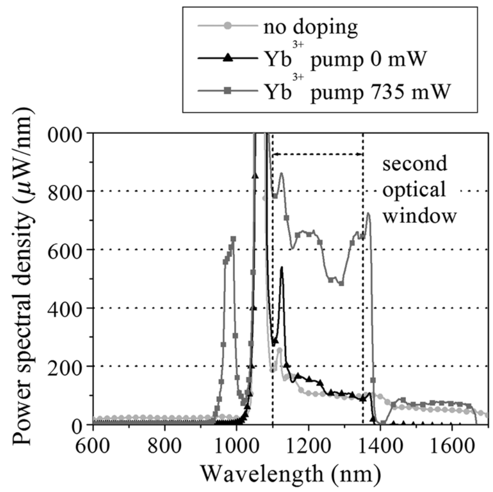

Fig. 8 SPD of the generated SC with and without pumping at a 976-nm wavelength and compared with the undoped PCF. The vertical lines indicate the second optical window.

integral power (for example, see the SC400-2 fianium[21]). If such a seed laser was used in an amplifier PCF setup, it would provide much higher SPD in the second optical window without exceeding the damage threshold of the fiber. Table 2 shows the optical parameters between 1100 and 1350 nm of the specified light sources in comparison to the results achieved.

Table 2 Comparison with commercial SC light sources in the second optical window (1100 to 1350 nm).

Model	Yb3+ PCF	Fianium SC400-2	Koheras Superk-Compact
Pulse length	2.1 ns	6 ps	1 ns
Integral power	161 mW	297 mW	19 mW
Repetition rate	12.5 kHz	20 MHz	25 kHz
Max SPD	0.85 mW/nm	1.5 mW/nm	0.07 mW/nm
Power stability	±1%	±1%	±4.5%

4 Conclusions

Amplification of a seed pulse was demonstrated inside an Yb3+ doped PCF with a zero dispersion wavelength near the excitation pulse's wavelength. This allowed us to increase the output power of the generated SC by nearly an order of magnitude without damaging the PCF. Because of the limiting factors of both the Yb absorption and the nano-powder process used to construct the PCF, the SC power increase was limited to a wavelength range between 1100 and 1370 nm, which makes this light source an optimal system for biological imaging in the second spectral window. When compared to a similar undoped PCF, the doped PCF displayed a significant increase in SPD in the second spectral window. An even larger gain in the second spectral region is expected when the parameters of the doped PCF, such as fiber length, doping concentration, pumping configuration, and seed laser repetition rate, are optimized. The pump radiation at 976 nm was not completely absorbed at maximum pump power. Increasing the doping level could help to drop the required fiber length or increase the amplification.[17]

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