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Gain-switched CW fiber laser for improved supercontinuum generation in a PCF

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Abstract: We demonstrate supercontinuum generation in a PCF pumped by a gain-switched high-power continuous wave (CW) fiber laser. The pulses generated by gain-switching have a peak power of more than 700 W, a duration around 200 ns, and a repetition rate of 200 kHz giving a high average power of almost 30 W. By coupling such a pulse train into a commercial nonlinear photonic crystal fiber, a supercontinuum is generated with a spectrum spanning from 500 to 2250 nm, a total output power of 12 W, and an infrared flatness of 6 dB over a bandwidth of more than 1000 nm with a power density above 5 dBm/nm (3 mW/nm). This is considerably broader than when operating the same system under CW conditions. The presented approach is attractive due to the high power, power scalability, and reduced system complexity compared to picosecond-pumped supercontinuum sources.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5295) Photonic crystal fibers; (140.3510) Lasers, fiber; (140.5560) Pumping; (190.4370) Nonlinear optics, fibers.

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1. Introduction

Supercontinuum sources based on the extreme broadening of laser pulses in nonlinear photonic crystal fibers (PCF) have been predicted to be a very interesting technology in the scientific as well as the industrial communities. Supercontinuum spanning the whole transmission window of silica with an average power of several Watts have been generated [1–3] and are now commercially available [4].

Typically, a pulsed laser is used for pumping a nonlinear PCF, but by using a continuous wave (CW) high-power fiber laser, the complexity of the system is reduced, and a higher average power and power spectral density can be obtained. The drawback of this system is the reduced peak power, which leads to less broadening and the need for longer fiber lengths. Especially the generation of light at shorter wavelengths than the pump wavelength is troublesome [5–12].

In state-of-the-art CW supercontinuum generation (SCG) pump powers of 100 W is routinely used and even a 400 W fiber laser has been tested [7–11]. Lengths of 20 m to 400 m of nonlinear

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PCF with reduced OH-loss are used and designs based on Ge-doped cores and tapered fibers have recently been investigated [7, 10, 11]. The improved performance of these designs is due to an increased nonlinearity by Ge-doping and a shift of the short and long wavelength edges depending on the design of the tapering [3, 13–16].

In Ref. [9] a 400 W laser was used for pumping pure silica PCFs and spectrum spanning from 1060 nm to the loss edge of silica (>2200 nm) was obtained. In another fiber with a zero group velocity dispersion wavelength (ZDW) only 20 nm shorter than the pump wavelength, a spectrum spanning from 600 nm to 1900 nm were obtained. In Ref. [11] a PCF with a Ge-doped core is pumped at a pump power of 100 W and a resulting spectrum spanning from 550 nm to ~2100 nm was demonstrated. By tapering the spectrum was extended down to 450 nm [11].

The benefits of CW pumping compared to pulsed pumping are the higher average power, simplicity of the setup, and a higher degree of flatness of the supercontinuum. The challenges are the long fiber lengths where the fiber loss can become significant, and the need for high average pump powers to increase the broadening and optimized fibers to increase the amount of light in the visible region [9, 11].

Slow on/off-modulation of the pump laser is often applied to reduce the thermal stress in the splices and at the end-facet of the nonlinear PCF due to the high average power [8, 9]. This modulation is typically done in the 100 Hz range and supercontinuum results are considered purely CW-pumped.

In this paper we present a new method to improve the SCG, which implies fast on/off modulation of the pump of the fiber laser [17]. The modulation is in the 100 kHz range and the underlying physical principle is to control the inherent relaxation oscillations of the fiber laser occurring shortly (few μs) after switching on the pump of the laser. By isolating the first and most powerful spike, a fast pulse train of high peak power, long-duration pulses is created. This is referred to as gain-switching [18, 19].

The first report on gain-switching was published shortly after demonstration of the first laser [18], and gain-switching has since been applied to for example Nd, Tm, and Yb-doped fiber lasers [19–22]. The development of high-power pump diodes and fiber laser technology has opened the possibility of using gain-switching efficiently to achieve high peak power pulses. These systems inherently have an all fiber-integrated format instead of the more common Q-switched lasers, which typically require free-space coupling to for instance an acousto-optical modulator [6, 23–25]. The completely monolithic system has the advantage of being mechanically and thermally robust, cost-effective, and simple. The generated pulse train presented here has, to our knowledge, the highest pulse energy and average power levels published using gain-switching of a fiber laser [20–22]. A higher average power of 321 W has been achieved by gain-switching of a diode laser and subsequent amplification by a chain of fiber amplifiers [26].

Gain-switching of a solid state Ti:Sapphire laser for SCG in a nonlinear PCF has been demonstrated with a resulting supercontinuum spectrum at the milliwatt level [27]. In Ref. [8] the modulation of a CW fiber laser at a repetition rate of 7.8 kHz was reported to 'enhances the continuum beyond that expected from the peak-power increase alone', which could indicate that the authors might have generated spikes. But so far spikes have not been described in the content of supercontinuum generation. Another approach was reported that did not rely on relaxation oscillations, but instead used a master oscillator power amplifier configuration with an acousto-optical modulator after the seed CW laser. Here short ns pulses were generated with hundred Watt peak power level [6], which are quite similar to the pulses described in the following, however such a system is more complex and is not monolithic.

We here present, to our knowledge, the first demonstration of a diode-pumped gain-switched CW fiber laser for SCG. The new approach reduces the average power level required for SCG while maintaining the benefits of CW pumping.

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2. Experimental Setup and Method

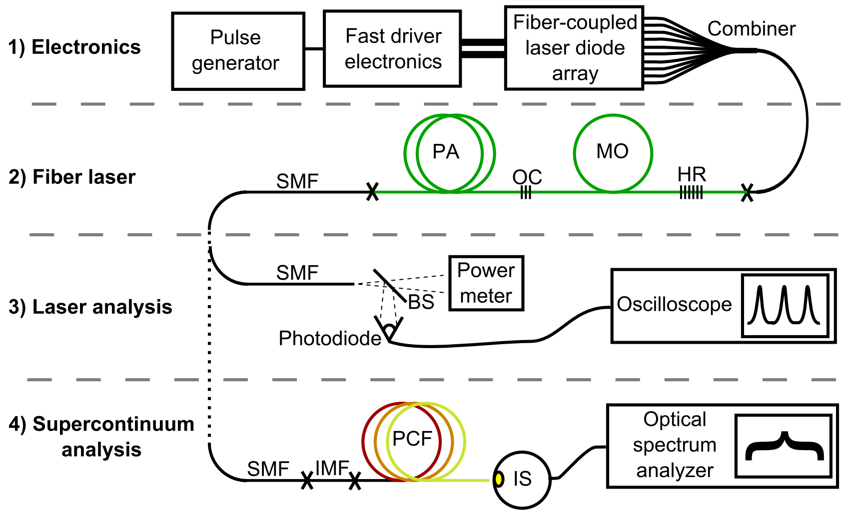

Fig. 1. The experimental setup for characterization of the fiber laser and the generated supercontinuum. The setup is for clarity split in four levels: (1) electronics, (2) fiber laser, (3) laser analysis and 4) supercontinuum analysis. The electronics consist of a pulse generator, a fast pump diode driver, and a pump diode array. The fiber-coupled pump diodes are combined into the Yb-doped airclad fiber laser. The high reflector (HR) grating and the output coupler (OC) grating construct the master oscillator (MO) and the rest of the fiber is a power amplifier (PA). A single-mode fiber (SMF) delivers either to the laser pulse analysis setup *or* it is spliced to an intermediate fiber (IMF), which is again spliced to the nonlinear fiber (PCF). The laser analysis uses a beam sampler (BS), a fast photodiode connected to an oscilloscope, and a power meter. The supercontinuum is measured through an integrating sphere (IS) by a fiber-coupled optical spectrum analyzer.

The experimental setup is illustrated in Fig. 1. The electronics consist of a high-power laser diode driver capable of driving the laser diode array in CW and pulsed operation. In pulsed operation a pulse generator controls the repetition rate and duty-cycle ($100\% \cdot t_{on} f$) of the current pulse. The fiber laser is pumped by 10 fiber-coupled 915 nm laser diodes rated to 10 W. The rise and fall times of the optical output of the laser diodes are $<0.5\ \mu$s.

The output multi-mode fibers of the laser diodes are spliced to a pump combiner. The combiner is then spliced to the active fiber, which is an airclad fiber with an Yb- and Ge-doped core. The fiber is single mode with a mode field diameter (MFD) of 15 μm, the airclad diameter is 250 μm, and the pump absorption is 0.5 dB/m at 915 nm. A high reflector (HR) grating and an output coupler (OC) grating are UV-written in the core. The OC is positioned 7 m into the fiber and the total length is 25 m. A single-mode fiber with MFD of 15 μm is spliced to the end of the active fiber to strip-off light in the cladding. The optical-to-optical efficiency of this system is 60% and with the current pump capacity a CW average output power of 64 W can be achieved [28, 29].

The fiber laser is characterized in the parameter space defined by pump power, pulse repetition rate, and duty-cycle. The convenience of the repetition rate/duty-cycle-space is that the duty-cycle scales the average power, which governs the thermal load on the system.

To characterize the fiber laser, the fiber is angle-cleaved and a beam sampler reflects a fraction of the output onto a 1 ns GaAs photodiode whose output photocurrent is measured by an oscilloscope. The transmitted light is measured by a thermal power meter. In the single-pulse

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regime the peak and average power for a given pump power are found by selecting the duty-cycle and increasing the repetition rate until only a single spike is emitted. A Gaussian fit is made to the temporal pulse and the full-width half-maximum (τ_{FWHM}) of this fit is defined as the spike duration.

For SCG a 100 m nonlinear PCF (SC-5.0-1040, NKT Photonics A/S) is spliced to the single-mode fiber by use of an intermediate fiber, which reduces the MFD from 15 μm to 4 μm to match the nonlinear PCF. The total splice loss is 0.7 dB. The fiber has a ZDW of 1040 nm and a nonlinearity of 11 $(\text{Wkm})^{-1}$ at the pump wavelength. The output of the fiber is launched into an integrating sphere. The visible and infrared spectra are measured with a 350-1750 nm or a 1200-2400 nm optical spectrum analyzer, respectively. The spectra are normalized to the output power and the visible and infrared spectra are stitched at 1500 nm.

The fiber laser can also operate in CW (by setting the duty-cycle to 100%), which means that the improvements of gain-switched pumping compared to CW pumping can be evaluated.

3. Gain-Switching of the Fiber Laser

In Fig. 2(a) the transient behavior of the fiber laser after instantaneous turn-on of the pump is shown. The pulses before the laser goes into CW operation are termed relaxation oscillations or spikes. In Fig. 2(b) the pump pulse width is set so that only the first spike is selected and the fiber laser is in gain-switching operation.

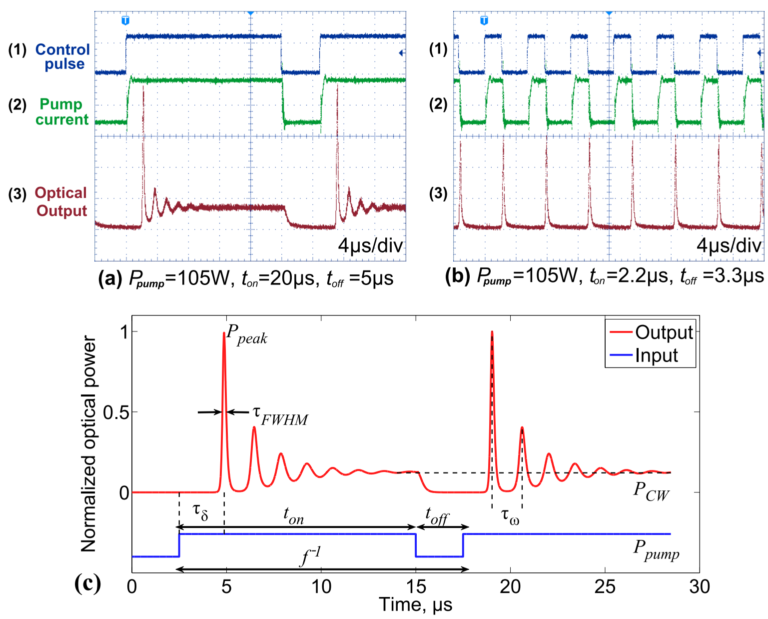

Fig. 2. Transient behavior of the fiber laser. In (a) and (b) oscilloscope traces of the electronic on/off modulation and fiber laser output are shown. (a) shows the relaxation oscillation regime ($t_{on} \gg \tau_\delta$). (b) shows the gain-switching regime for which t_{on} are selected by fulfilling $t_{on} \approx \tau_\delta$. In (c) the transient behavior is illustrated and the characteristic parameters are defined, such as the spike delay time τ_δ, oscillation period τ_ω, pump power P_{pump}, first spike peak power P_{peak}, full width half maximum width τ_{FWHM}, CW power level P_{CW}, pump pulse width t_{on}, off-time t_{off}, and repetition rate f.

In Fig. 2(c) definitions of characteristic parameters are given. The spike delay time τ_δ is the time between when the pump is turned on and the first spike. The oscillation period between

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the spikes is τ_ω. For a given pump power P_{pump} a certain peak power of the first spike P_{peak} is obtained and the duration of this is defined as the full width half maximum τ_{FWHM}. If the pump pulse width t_{on} is much longer than the decay of the relaxation oscillations the laser goes into CW operation with an output power of P_{CW}. If the pump is off for a time period of t_{off} the cavity is emptied with the cavity decay time. The process repeats with the repetition rate f.

To be able to analyze the peak power of the pulses a Gaussian fit to the pulse profile is calculated as seen in Fig. 3. The peak power is then found as $P_{peak} = P_{ave}(f \cdot \tau_{FWHM})^{-1}$ where P_{ave} is the measured average output power of the fiber laser and the pulse duration τ_{FWHM} is determined by the fit. The pulses do not have a perfect Gaussian shape but the method allows for an approximate determination of the peak power. The oscillations at the peak of the pulse are longitudinal mode beating, because a Fourier transform of the pulse gives lines at multiples of the longitudinal mode spacing of $\tau_{rt}^{-1} = 14.2$ MHz. The cavity round trip time is $\tau_{rt} = 2nL/c_0 =$ 70 ns, where $L = 7$ m is the cavity length, n the refractive index, and c_0 is the light speed. These stochastic beatings are about 35 ns ($0.5\tau_{rt}$) in duration and result in periodically increased peak power, which means that they could potentially be advantageous for SCG.

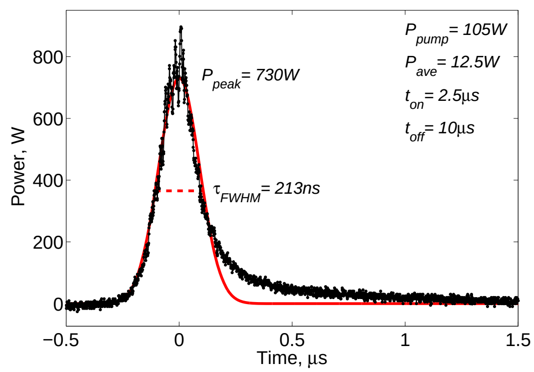

Fig. 3. Peak power determination of the pulse by a Gaussian fit. The pulse is obtained with the parameters to the upper right. The peak power is estimated to be 730 W and the duration is 213 ns. The spikes at the peak are longitudinal mode beatings.

The spectral properties of the fiber laser have been characterized and the center wavelength is 1063.9 nm. The bandwidth at CW operation is measured to be 0.1 nm and during gain-switching it increases to 0.4 nm.

By using the procedure of selecting the first spike and analyzing the peak power by a Gaussian fit, the gain-switching properties of the fiber laser are analyzed. The result at the maximum pump power of 105 W is shown in Fig. 4. The pump power is fixed at 105 W to give the highest possible peak power and by varying the duty-cycle the average power is changed. The resulting t_{on} and t_{off} are shown in the lower part of Fig. 4.

3.1. Discussion

The shape of the peak power curve in Fig. 4 will be described in the following. At the lowest average output powers the pump pulses are separated by long off-times. The limiting situation of this is given by a completely relaxed laser cavity pumped by a pump pulse. Here the pump has to excite carriers to reach threshold before lasering occurs. This costs pump energy, hence the peak power of the first spike is reduced. The characteristic time for a completely relaxed cavity is given by the upper state life time of the Yb-ions τ_{Yb}, which is 600-800 μs depending among others on the doping concentration [30]. By these arguments the region of reduced peak

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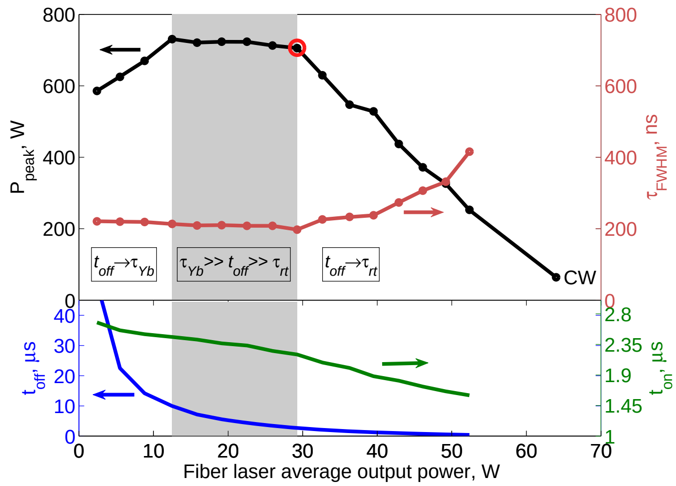

Fig. 4. The gain-switching power characteristics of the fiber laser at maximum pump power of 105 W. The peak power (P_{peak}) and width (τ_{FWHM}) of pulses are shown. The optimum regime regarding peak power is in-between the slow; $t_{off} \to \tau_{Yb}$ and the fast; $t_{off} \to \tau_{rt}$ regimes. The off-time t_{off} and the pump width t_{on}, which is set equal to the spike delay ($\tau_\delta = t_{on}$), are shown in the lower part.

power at lowest average powers can be explained by too long off-time in which the system approaches the relaxed state ($t_{off} \to \tau_{Yb}$).

At the highest average output power the off-time is decreased. If the off-time approaches the cavity decay time, the cavity still contains a large amount of photons at the beginning of a new pump cycle. Therefore, the initial conditions for the relaxation oscillations are different and it results in longer durations of the spikes. This situation characterizes the high average power region and can explain the reduction in the peak power. The regime can be described by $t_{off} \to \tau_{rt}$ where the cavity round trip time $\tau_{rt} = 70$ ns determines the cavity decay time.

From this discussion the requirements for efficient gain-switching of a fiber laser can be put forward: the pump pulse width should be close to the spike delay time ($t_{on} = \tau_\delta$), and off-time should be much shorter than the life time of the excited state ($t_{off} \ll \tau_{Yb}$) and much longer than the photon decay time determined by the cavity round trip time ($t_{off} \gg \tau_{rt}$). Furthermore, the pump rise and fall times should be much shorter than the spike delay time. The laser efficiency during gain-switching is essentially the same as the CW efficiency.

For SCG we require the highest peak power to obtain the broadest bandwidth and for a fixed peak power we require the highest average power to get the highest power spectral density in the supercontinuum spectrum. Given the plateau of constant peak power observed in Fig. 4, we therefore select the optimum point of operation as the point marked by red in Fig. 4. Here, gain-switching of the fiber laser can yield a train of pulses with more than 700 W peak power and duration around 200 ns, when operated at 105 W of pump power, a repetition rate of 210 kHz, and a duty-cycle of 45%, which corresponds to $t_{on} = 2.1$ μs and $t_{off} = 2.6$ μs. The resulting average power is 29 W and the pulse energy is 150 μJ. The generated pulse train has, to our knowledge, the highest pulse energy and average power levels published using a diode-pumped gain-switched fiber laser [20–22].

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4. Supercontinuum Generation

The process of SCG in optical fibers is well-understood [1]. For picosecond and longer pulses, and when pumping close to the ZDW but in the anomalous dispersion region of a nonlinear PCF, the supercontinuum is initiated by the modulation instability, which creates a number of solitons in the anomalous dispersion region and a large amount of dispersive waves in the normal dispersion region below the pump wavelength. The solitons redshift due to Raman scattering and can through four-wave mixing trap the dispersive waves causing them to blueshift resulting in group velocity matching of the spectral edges [1–3, 14, 31–33].

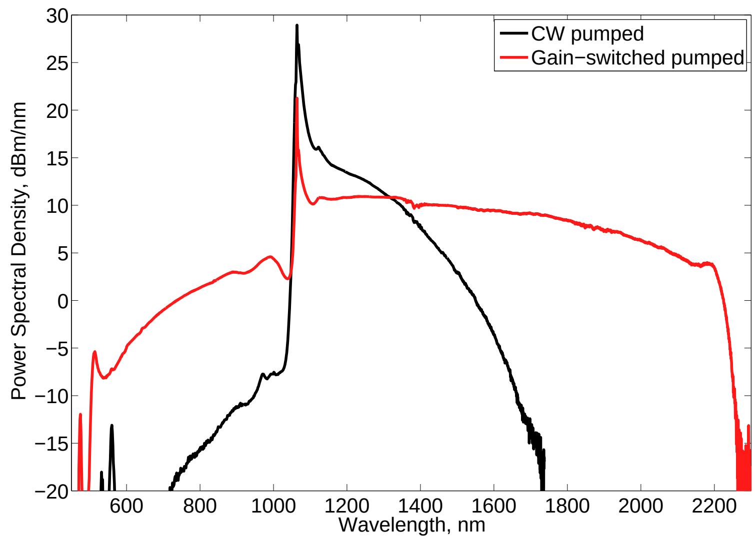

Fig. 5. Supercontinuum generation in the 100 m long nonlinear PCF (SC-5.0-1040) pumped by the fiber laser in CW operation and in the optimum gain-switching operation with 600 W coupled peak power in 200 ns pulses. The coupled average power of both inputs is 25 W and the output powers are 17 W and 12 W for CW and gain-switched pumping, respectively.

In Fig. 5 we show the supercontinuum results obtained by pumping the nonlinear PCF with the fiber laser in CW and gain-switching operation. The settings used for gain-switching are marked in Fig. 4 with the red dot. The coupled peak power is 600 W and the coupled average power is 25 W. For comparison a coupled average power of 25 W is also used for CW pumping.

When applying gain-switching, the spectrum spans from 500 nm to 2250 nm (-10 dBm/nm level), and the total output power is 12 W. The infrared part is particular flat and has a flatness of 6 dB over a bandwidth of more than 1000 nm with a power density above 5 dBm/nm (3 mW/nm). The maximum power spectral density (when ignoring the pump) is 11 dBm/nm (12 mW/nm) at 1250 nm and the bandwidth at a power spectral density above 0 dBm/nm (1 mW/nm) is 1500 nm. The infrared edge of the spectrum is determined by the loss edge of silica. By calculating the dispersion properties of the nonlinear PCF it has been confirmed that the visible edge is group-velocity matched to the infrared edge. This means that the trapping process is responsible for the visible edge [31–33]. The short wavelength side of the pump has a flatness of 6 dB over a bandwidth of 365 nm.

When operating under CW conditions the spectrum is spanning from 950 nm to 1650 nm (-10 dBm/nm level) with an output power of 17 W. The part of the spectrum above 5 dBm/nm spans only 400 nm. Due to the much lower peak power, compared to gain-switched pumping, the modulation instability is less efficient and high-energy solitons that can redshift to the loss

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edge are not formed. Notice the lack of visible light generation, which is typical for CW SCG when not pumping very close to the ZDW. The average output power when operating in CW is higher because no light is generated at the infrared-loss edge.

In comparison to reported CW results, where much more powerful CW fiber lasers were used, our generated supercontinuum spectrum is among the broadest which means that gain-switching allows more efficient use of the fiber laser [9, 11]. Furthermore, the system setup is much simpler than the typical ps-pumped supercontinuum sources.

5. Conclusion

We have demonstrated SCG in a nonlinear PCF using a gain-switched high-power CW fiber laser. The study is motivated by the possibility of power scalability and reduced complexity compared to picosecond-pumped supercontinuum, and the fact that the very high average pump power levels and highly optimized PCFs necessary for typical CW SCG can be avoided.

Modulating the pump diodes coherently with the relaxation oscillations of the fiber laser resulted in the so-called gain-switching operation. The pulse train generated through gain-switching has been determined to have a peak power of more than 700 W, a duration around 200 ns, and a repetition rate of 200 kHz, resulting in a high average power of almost 30 W.

Supercontinuum generation in a commercial nonlinear photonic crystal fiber by CW-pumping and pumping with the gain-switched fiber laser were compared. The spectrum generated by the gain-switched pulse train spanned from 500 to 2250 nm, with a total output power of 12 W, and high infrared power spectral density above 5 dBm/nm (3.1 mW/nm) over a bandwidth of more than 1000 nm with a 6 dB flatness. This spectrum is considerably broader than when CW-pumping the same nonlinear fiber.

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