Picosecond fiber MOPA pumped supercontinuum source with 39 W output power

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Abstract: We report a picosecond fiber MOPA pumped supercontinuum source with 39 W output, spanning at least 0.4-2.25 µm at a repetition rate of 114.8 MHz. The 2m long PCF had a large, 4.4 µm diameter core and a high-delta design which led to an 80% coupling efficiency, high damage threshold and rapid generation of visible continuum generation from the picosecond input pulses. The high and relatively uniform power density across the visible spectral region was ~31.7 mW/nm corresponding to peak power density of ~12.5 W/nm for the 21 ps input pulses. The peak power density was increased to 26.9 W/nm by reducing the repetition rate to 28 MHz. This represents an increase in both average and peak power compared to previously reported visible supercontinuum sources from either CW pumped or pulsed-systems.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.4370) Nonlinear optics, fibers; (250.4480) Optical amplifiers.

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1. Introduction

Supercontinuum generation (SCG) has been an exciting research field over the past few years with new advances being reported on all aspects of the technology [1,2]. The invention of Photonic crystal fiber (PCF) with high non-linearities and tailored dispersion profiles first enabled SCG pumped by a femtosecond laser oscillator without complex amplification systems, and led to supercontinuum sources becoming a widely used laboratory tool [3–5]. The initial work on visible SCG used Ti:Sapphire lasers, but the high maintenance costs and limited average power led to the development of alternative pump lasers. In particular, fiber lasers have become the standard source in commercial SCG products (e.g. Fianium, Koheras).

Where applications require high average power SC sources with useful power levels available after spectral slicing further source developments are still required. High average power SCG has been reported by Travers *et al.* [6]. They demonstrated a visible SC source pumped by a 400 W CW laser at 1.07 µm with either 50 W average output power in the region of 1.05 – 2.2 µm or 28 W covering 0.6 – 1.9 µm spectral region with power densities varying between 2 mW/nm in the visible and ~30 mW/nm in the infrared. While CW pump sources are simpler than pulsed sources, they do have some disadvantages such as the long lengths of PCF required for the continuum to form and because a splice with just a few percent loss implies several Watts of heat load due to the high average power of the pumps. As has been demonstrated by Stone and Knight [7], a pulsed source enables higher peak power visible SCG to be produced and the pulsed driving format also enables synchronization to a lock-in detection circuit. However, the pulse-pumped visible SCG sources that have been reported have lower average power compared to CW sources [7–10].

Here we report a picosecond fiber MOPA pumped SC source with a high optical-to-optical conversion efficiency of up to 74%, covering a spectral range of 0.4-2.25 µm. The maximum average output power was 39 W at an incident pump power of 57 W and repetition rate of 114.8 MHz. The spectral power density of more than 30 mW/nm was relatively uniform across the visible region. At a reduced repetition rate of 28 MHz, we obtained higher peak spectral densities of 26.9 W/nm at visible wavelengths but with a slightly lower average power of 20 W. The pump laser was a robust, tunable repetition-rate, Yb-doped fiber MOPA with a 21 ps gain-switched seed [11]. To our knowledge, the visible spectral power density at the output of our system is higher than previous results from either CW or pulsed SC sources.

Following Stone and Knight's demonstration that a high air-fill-fraction PCF design with core diameter of 4.2 µm–4.7 µm range produced more continuum in the 400-450 nm wavelength range than low air-fill designs such as endlessly single mode fibers, we chose a 4.4 µm core diameter, high-delta PCF for the continuum generation [7]. The large core diameter led to a coupling efficiency of up to 80% and an increased optical-to-optical conversion efficiency when compared to CW pumped sources [6]. The large core also provided a higher damage threshold than smaller core fibers and the dispersion profile led to rapid generation of visible continuum and enabled the use of 2 m fiber length. In addition to considering the structural parameters of the PCF, increasing the blue-shift of the SCG is also possible by modifying the glass composition of the fiber [12].

This paper is divided into five sections. The experimental setup is presented in section 2. The fiber characteristics and highest average power supercontinuum results are provided in section 3. The highest peak power results were obtained by reducing the repetition rate and are shown in section 4. The conclusions are presented in section 5.

2. Experimental setup

Figure 1 shows the schematic of our setup. The YDFA MOPA pump laser system generated linearly polarized, diffraction-limited, 21 ps pulses at user selected repetition rates ranging from 14 MHz to 910 MHz and with an average output power up to 100 W as described previously [11]. The corresponding maximum pulse energy and peak power at the repetition rate of 114.8 MHz relevant to the SC experiments reported here were 0.8 µJ and 39 kW.

A 0.15 nm linewidth gain switched semiconductor diode at 1060 nm running at a repetition rate of 910 MHz was used for the seed. The repetition rate was down selected using

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an electro-optic modulator pulse-picker. Fiberised pre-amplifiers boosted the power to ~1 W prior to coupling into the 5.7 m long, polarization maintaining (PM) power amplifier. The amplifier fiber had a 340 µm inner cladding diameter with NA of 0.45 and a 25 µm core diameter with NA of 0.055 (Nufern). Although the fiber core can support 2 transverse modes, robust single mode operation was obtained by tapering the input end of the amplifier to a diameter of 125 µm before splicing on to the single mode fiber pigtail of the isolator at the input. The power amplifier was end-pumped using a commercially available 975 nm diode stack with a maximum pump power of 167 W.

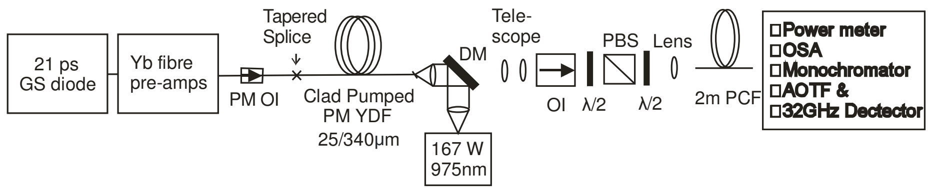

Fig. 1. Schematic diagram of the Yb-doped fiber MOPA and launch to the PCF.

The output beam from the MOPA had an M^2 of ≤1.1 and the stability of the result was ensured by the tapered splice. The output polarization extinction ratio (PER) was better than 19 dB after the MOPA but the optical elements used inside the bulk isolator degraded the PER to a certain extent. A half wave plate (HWP) and a polarization beam splitter were used to eliminate the light coupled into the other polarization axis inside the isolator. The total insertion loss of the isolator, HWP and PBS was approximately 35%. Another HWP before the coupling lens enabled alignment of the polarization axis of the beam to a principal birefringence axis of the PCF. Spectra were recorded using a fiber-coupled OSA (ANDO AQ6315) in the 400-1750 nm range and a free-space coupled monochrometer and PbS detector in the 1.75-3.5 µm range.

3. Fiber characteristics and high average power supercontinuum results

The PCF used for the SCG was an all silica structure fabricated using the stack and draw technique and had a core diameter of ~4.37 µm and a high air-fill-fraction in the cladding as shown by the photograph in Fig. 2(a). The zero dispersion wavelength is at ~1012 nm such that the wavelength of our picosecond pump source lies in the anomalous dispersion region. The dominant mechanisms leading to spectral broadening are likely to be modulation instability, leading to a soliton continuum and subsequent blue expansion due to soliton trapping [1,7,13]. The dispersion data shows the experimentally measured points overlaid on the curve calculated by modeling using a commercial finite element module (COMSOL Multiphysics) based on the optical micrograph of the fiber (shown inset). The pitch (Λ) of the air holes was measured to be 5.29 µm with d/Λ ~0.956. Figure 2(b) shows the loss of the PCF measured using the cut-back method. The loss was ~0.175 dB/m at the 1.06 µm pump wavelength and ~0.5 dB/m at the OH loss-peak in the 1.35-1.40 µm region.

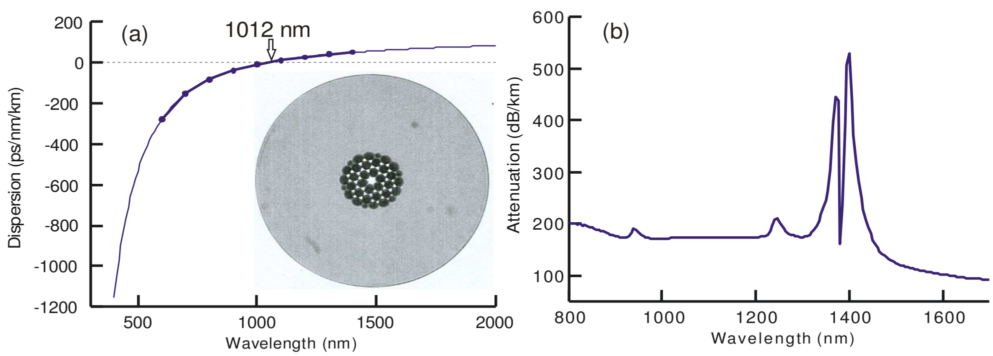

Fig. 2. (a) Dispersion profile of the PCF. (b) Measured attenuation data.

The launch optics comprised a telescope that matched the beam size to a high-NA aspheric coupling lens at the input of the fiber. Several focal lengths were tested before finally selecting an f = 3.1 mm aspheric lens. Figure 3 shows the average output power of the SC source as a function of the incident pump power when operating at the 114.8 MHz repetition rate at which we obtained the highest power continuum of 39 W. The launch efficiency was > 80% at incident powers below 30 W. We believe that the observed roll-off in output power vs. incident pump power was primarily due to beam quality degradation inside the bulk isolator with increasing power. The far field pattern of the output beam is shown inset to Fig. 3 (top). Note that the central region of the image is saturated in order to show the low intensity side-lobes [14]. The lower inset to Fig. 3 shows the separate components of the visible spectrum that were observed after passing the continuum through a prism.

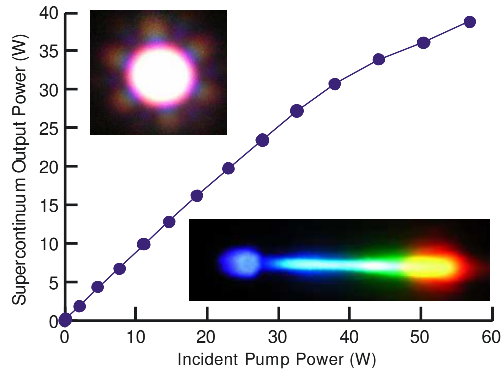

Fig. 3. Supercontinuum output power vs incident power. Inset shows the far field pattern of the output beam and prism separated white light.

We found that the highest continuum output power was limited by damage to the fiber output facet. (We are uncertain about the mechanism involved although we note that damage caused by UV absorption is a possible contributing factor [15].) In future an angle-polished end-cap could be used to avoid back-reflections and expand the mode, but we did not have the mechanics available in the short term to achieve the angle necessary for this high NA fiber. We tested the system at high power for ~20 minute periods at SCG powers of up to ~35 W and we did not observe any significant change in the output power, output spectrum or mode shape. At the maximum 39 W power level the heat load on the fiber input prevented us from operating for extended periods because of drifting of the launch optics. However we also ran the system daily for ~20-30 minute periods for over a week of operation with reduced repetition rates at the 20 W level such that the peak power was similar to that of the 39 W SCG results and again we did not observe any photodarkening of the SCG fiber.

Figure 4 shows the spectral evolution at an incident power level of 0.15 W, 11 W and 57 W at a repetition rate of 114.8 MHz. The labels show the peak powers of the launched pump pulses. We observed that the colour of the continuum spectrum evolved along the fiber and when operating with a maximum average power the continuum was visibly white after 1.5 m. However, optimization using cut-back measurements showed that the spectral flatness improved using a 2.0 m length of PCF and therefore a 2.0 m length was used for the results shown above. Longer fiber lengths produced lower output powers due to the fiber loss. Numerical integration of the continuum spectrum indicated that just 12% of the power remained at the pump wavelength. The spectrum covered the range from 400 nm to 2300 nm with spectral flatness across the visible region of better than 10 dB and a blue peak at a wavelength of 430 nm (shown in Figs. 3 and 4).

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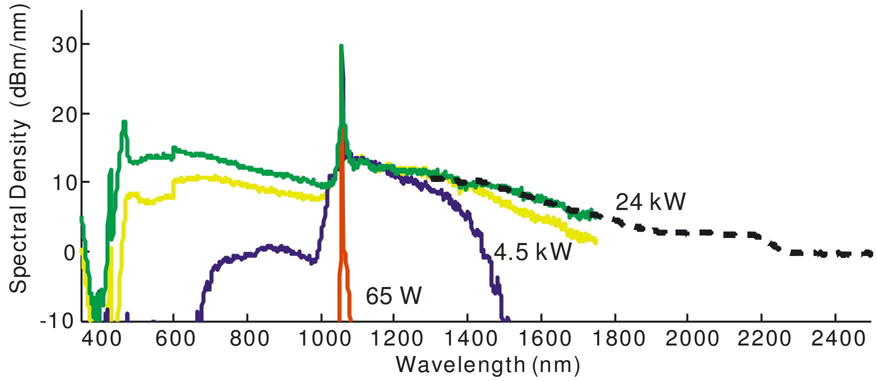

Fig. 4. Supercontinuum evolution in a 2 m long PCF at 0.15 W, 11 W and 57 W of incident pump power at repetition rate of 114.8 MHz. Solid lines – OSA measurements, dashed line– measurements with monochrometer and PbS detector. (The top lines in green/yellow show spectra with input polarization aligned to orthogonal birefringence axes.)

We recorded the continuum spectra with various orientations of the half-wave-plate at the fiber input. We first measured the angles of the fiber birefringence axes by using low energy pulses and an analyzer PBS at the PCF output. The measured birefringent beatlength was 35 mm and the weak birefringence was due to the relatively large core. At the maxium 39 W supercontinuum power level, the broadest continuum was produced with the polarization aligned to one of the principal axes and the narrowest spectrum was produced on the orthogonal axes. The variation in the spectra with the input polarization aligned to the orthogonal birefringence axes can be seen in Fig. 4.

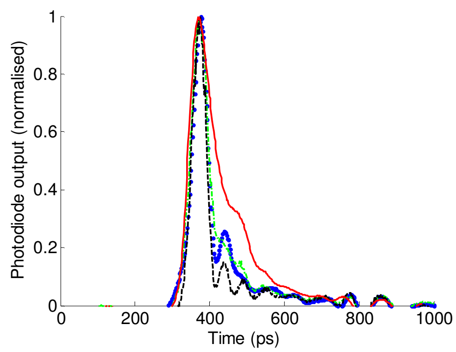

Fig. 5. Pulse shape of transmitted low power pump (blue dotted line), filtered at 1186.6 nm (green dash dotted line), filtered at 1317.6 nm (black dashes) and broadband (solid red line).

Figure 5 shows the temporal profiles of the optical pulses at the output of the 2 m PCF (shown in Fig. 2) measured using a 20 ps resolution InGaAs photodiode and sampling scope. The broadest pulse corresponds to the full bandwidth of SC spectrum incident on the diode. When the pulses were coupled onto the orthogonal fiber axis, the main peak was delayed and appeared at the position of the shoulder to the rear of the pulse, so we attribute that shoulder to stray power coupled onto the orthogonal fiber axis. The shorter pulse shown by the blue dotted line in Fig. 5 was obtained with lower pump power (PCF output of 50 mW). We also filtered the continuum spectra with an accousto-optic tunable filter (AOTF) to produce 1.2 nm bandwidth spectra at 1186.6 nm and 1317.6 nm and the pulse durations were within the measurement resolution (Fig. 5), confirming that the wavelength shifting had not increased the input duration substantially. (Note that the extended tail was an artifact of the diode/scope system since it was also seen in an impulse response measurement using clean 200 fs pulses.)

For comparison we tested two commercially available silica PCFs produced by NKT Photonics (formerly Crystal Fiber) using our high power MOPA as the seed. The larger core

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fiber (SC-5.0-1040 data available from www.nktphotonics.com) had a mode field diameter (MFD) of 4 µm and ZDW at 1040 nm and with a 10 m length the maximum transmitted power at the 128 MHz repetition rate was 10 W with a yellow, rather than white colour at the output and a minimum wavelength of 489 nm. We did not perform cut-back measurements on the fiber but we observed the colour evolution on the spool and a minimum length of between 5 m and 7 m was required for the yellow colour to develop. In comparison, the fiber fabricated at CGCRI had a more rapid onset of visible continuum, improved power transmission and blue spectral components extending to 409 nm. The second commercial fiber tested (NL-1050-ZERO-2) had a smaller core with MFD of 2.2 µm and ZDWs at 975 nm and 1125 nm and in this case no visible light was generated at the maximum transmitted power of 1 W (limited by facet damage).

4. High peak power supercontinuum results

Since the maximum average power was limited by thermal damage, we tested the fiber with lower repetition rates which produce higher pulse energies for a given average power. This led to an increase in the input peak power density before thermal damage or output facet damage became a problem and the limit on continuum power was then due to *input* facet damage due to the high peak intensity. The peak power for facet damage when using the f = 3 mm launch lens was ~40 kW +/− 3 kW at repetition rates between 14 MHz and 56 MHz. In future, power scaling may be therefore possible by using a mode-expanding end-cap at the input to the fiber in order to reduce the intensity at the air/glass interface.

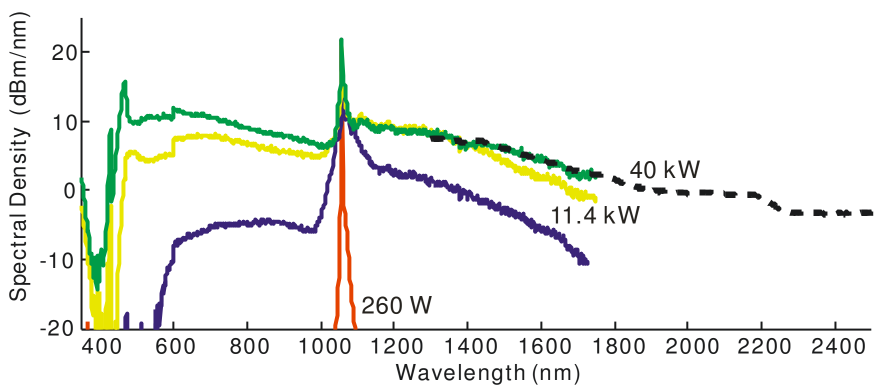

Fig. 6. Supercontinuum evolution in a 2 m long PCF at 0.15 W, 7 W and 25 W of incident pump power at repetition rate of 28 MHz. (The top lines in green/yellow show spectra with input polarization aligned to orthogonal birefringence axes. Linestyles as in Fig. 4.)

Figure 6 shows the SCG obtained at a repetition rate of 28 MHz. The maximum average power was 20 W and the peak power spectral density across the visible of 26.9 W/nm compared to 12.5 W/nm for the highest average power results in Fig. 4. The overall profiles of the continuum spectra are similar at both repetition rates but in Fig. 6, the visible power density is ~10 dBm/nm below the input wavelength peak whereas in Fig. 4, the visible power density is ~15 dBm/nm below the peak so there is more effective conversion of pump to visible wavelengths at the higher peak power. As with the high average power results (Fig. 4.) the variation in the spectral bandwidth with the input polarization was investigated and we found that with the maximum input peak power of 40 kW, the SCG was broadest and narrowest with the polarization aligned to the fiber's orthogonal birefringence axes with the variation in spectra shown in Fig. 6.

5. Conclusion

We have successfully demonstrated a picosecond fiber MOPA pumped high power supercontinuum source covering at least 0.4-2.25 µm spectral region. Average output powers as high as 39 W with > 80% launch efficiency and 87% pump depletion were achieved at a repetition rate of 114.8 MHz. A power density of up to 31.7 mW/nm with good uniformity

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was measured across the full visible spectral range. At a reduced repetition rate of 28 MHz the peak power spectral density in the visible was 26.9 W/nm with 93% pump depletion, average power of 20 W and an overall conversion efficiency of 74%.

Peak power scaling may be possible using a shorter fiber length fiber with an end-cap to avoid input facet damage so that higher energy input pulses could be used. Then we expect a shorter length of fiber would produce a similarly broad continuum but with reduced absorption losses. Further improvements would be expected with a fiber that was treated to remove the OH impurities.

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