High repetition rate tunable femtosecond pulses and broadband amplification from fiber laser pumped parametric amplifier

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Abstract: We report on the generation of high energy femtosecond pulses at 1 MHz repetition rate from a fiber laser pumped optical parametric amplifier (OPA). Nonlinear bandwidth enhancement in fibers provides the intrinsically synchronized signal for the parametric amplifier. We demonstrate large tunability extending from 700 nm to 1500 nm of femtosecond pulses with pulse energies as high as 1.2 μJ when the OPA is seeded by a supercontinuum generated in a photonic crystal fiber. Broadband amplification over more than 85 nm is achieved at a fixed wavelength. Subsequent compression in a prism sequence resulted in 46 fs pulses. With an average power of 0.5 W these pulses have a peak-power above 10 MW. In particular, the average power and pulse energy scalability of both involved concepts, the fiber laser and the parametric amplifier, will enable easy up-scaling to higher powers

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (190.4970) Parametric oscillators and amplifiers; (999.999) Photonic crystal fibers.

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1. Introduction

Sources of tunable ultrashort laser pulses are essential tools for probing fast phenomena in physics, chemistry and biology. Kerr-lens modelocked Ti:Sapphire lasers[1] have proven to be very reliable sources of femtosecond pulses and ”turn-key” devices supplying sub-20 fs are now commercially available[2]. However, in spite of the outstanding performance of these lasers, the tunablity is restricted to the region around 800 nm and the second harmonic around 400 nm. The limited tuning range can be greatly expanded through optical parametric amplification (OPA) which has become a widely used technique[3]. In an OPA coupling of three waves via the nonlinear polarization enables photons from the intense pump wave to be efficiently converted into (lower-energy) signal photons and the same number of so-called idler photons. Such a scheme requires fulfilled energy and momentum conservation, also termed as phase-matching, determining the interacting wavelengths and in particular the tunability and bandwidth of the parametric amplification.

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It has been demonstrated that waiving of traditional collinear pumping geometry leads to a significant increase of the phase-matched bandwidth which can be obtained in OPA[4]. As a result, ultrashort laser pulses are now routinely generated throughout the visible and near infrared spectral region with high efficiency employing non-collinear parametric amplifiers (NOPA)[3, 5, 6].

A typical NOPA is driven by an amplified Ti:Sapphire laser system delivering 100-200 fs pulses with energies up to a few mJ. The high pulse energy and resulting peak power ensure highly efficient nonlinear conversion in the amplifying stages and several tens of μJ can usually be obtained across the desired wavelength range[3]. However, the average power from the Ti:Sapphire systems is limited by the thermal load on the gain crystal as thermal lensing deteriorates the beam quality. Without special precautions the maximum average power is therefore of the order of a few Watts[7]. In contrast, the parametric amplification itself does not suffer from thermal effects. The fulfilled energy conservation and high optical quality of the nonlinear crystals ensure that heating of the crystal is minimal. For that reason parametric amplification is highly suited for high repetition-rate and high average power applications.

In this context fiber lasers and amplifiers represent an interesting alternative to the conventional Ti:Sapphire-based systems as they can supply high average powers as well as high pulse energies[8]. Due to excellent heat dissipation and strong confinement of the light in fibers, diffraction limited beam quality can be obtained even with continuous wave powers well above 1 kW[9]. Additionally, the high conversion efficiencies (up to 80%) from low-brightness laser pump diodes[10] enable a great reduction in price as well as complexity of such systems. Short-pulse fiber lasers are therefore predestinated pump sources for high repetition rate parametric amplifiers.

In this contribution we report the implementation of a 1 MHz repetition rate parametric amplifier pumped by a chirped pulse fiber amplification system. With the present setup a single pass fiber amplifier is used and yet femtosecond pulses with energies above one μJ can be obtained and tunability in the range < 700 nm to > 1500 nm has been observed. The broadband signal is generated in a photonic crystal fiber, providing a reliable and nearly flat supercontinuum. Furthermore, we demonstrate short-pulse amplification by amplifying a self-phase-modulation (SPM) broadened spectrum at degeneracy and subsequently re-compressing it to a pulse duration of 46 fs. To our knowledge this represents the first demonstration of μJ level and MHz repetition rate ultrashort laser pulses in a power scalable architecture.

2. Experimental Setup

The high repetition rate tunable femtosecond source consists of a single stage parametric amplifier pumped by a frequency doubled ytterbium-doped fiber based chirped pulse amplification system. The seed is provided by a supercontinuum generated in a photonic crystal fiber (PCF). The experimental setup is shown in Fig. 1: An Yb:KGW oscillator (Amplitude Systemes tpulse 200) delivering transform-limited 380 fs, sech^2 pulses at a repetition rate of 9.8 MHz and pulse energies up to 250 nJ is used to seed a fiber amplifier consisting of 1.2 meters of a large-mode-area double clad ytterbium-doped photonic crystal fiber[11]. The fiber has a 40 μm core and is intrinsically single-moded with a NA of 0.03 at 1030 nm. The extremely low nonlinearity of the amplification fiber allows, to a large extent, avoidance of restricting nonlinear effects by stretching the pulses to only 50 ps. Therefore, the stretcher employing a gold-coated grating with 1200 lines/mm, stays compact in size. After the stretcher an acousto-optic modulator (AOM) is used to lower the repetition rate to 1 MHz before coupling into the amplifying fiber. The fiber is pumped from the opposite end by a fiber coupled diode laser emitting at 976 nm.

After amplification the pulses are re-compressed by a pair of fused silica transmission gratings[12] with 1250 lines/mm. Figure 2 shows the compressed power at 1028 nm as function

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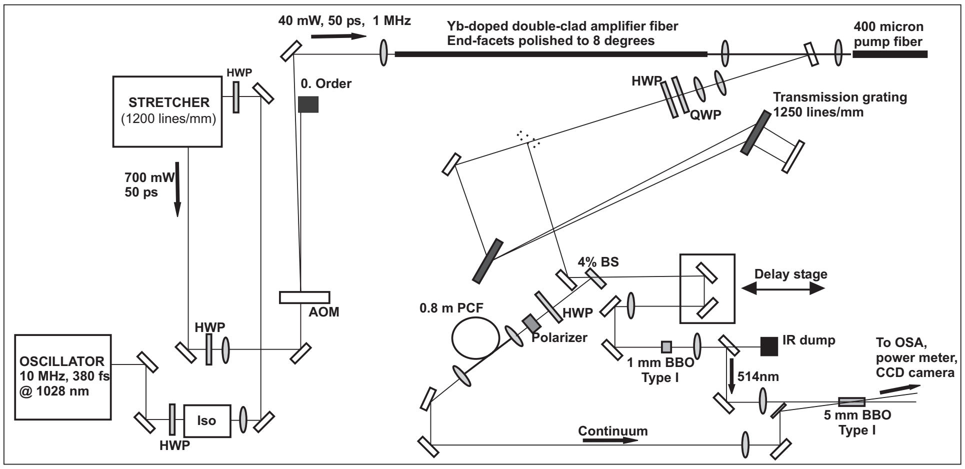

Fig. 1. Experimental setup of the high repetition rate tunable femtosecond source. Iso: optical isolator, HWP: half-wave plate, QWP: quarter-wave plate, AOM: acousto-optic modulator, BS: beam splitter, PCF: photonic crystal fiber, OSA: optical spectrum analyzer

of pump power coupled into the fiber. A slope efficiency of 48% is obtained taking into account the efficiency of the amplifier and the compressor.

The compressed pulses are then divided by a 4% beam-splitter. The weak signal is coupled into a 80 cm long PCF with a 3μm core diameter and zero-dispersion wavelength at 975 nm (Crystal Fibre A/S). A half-wave plate and an isolator are used to control the power launched into this fiber. The resulting supercontinuum stretches from about 600 nm to 1600 nm and provides a signal for the OPA of high spectral density and excellent beam quality. The remaining light is frequency doubled in a 1 mm BBO crystal cut for type I phase-matching with a conversion efficiency above 60%. The measured second harmonic average power as a function of diode power is shown in Fig. 2 as well. Based on measured autocorrelation traces of the IR pulses and simulations made with the freely available SNLO software[13], the pulse duration of the second harmonic (SH) was estimated to be 700 fs. Finally, the super continuum and the SH are overlapped non-collinearly in a 5 mm long BBO crystal (type I) and temporal overlap is obtained by means of a delay stage. The SH beam is focused to a spot-size of roughly 100 μm

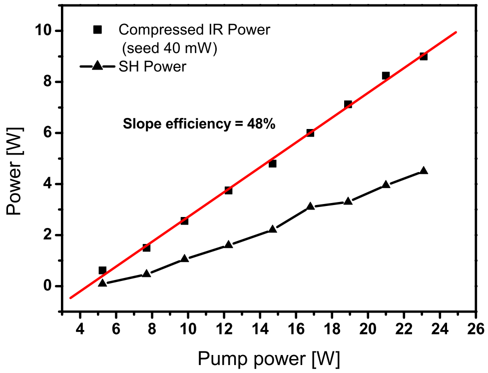

Fig. 2. Slope efficiency of the fiber amplifier and resulting second harmonic power as functions of pump power coupled into the fiber.

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which enables peak-intensities of up to 70 GW/cm^2 while ensuring a proper spatial overlap with the seed.

3. Tunable parametric amplification

3.1. Broadband phasematching

Figure 3(a) shows the calculated broadband phase-matching curve for NOPA in a BBO crystal pumped at 514 nm. At an assumed non-collinearity angle of 2.6° (internal angle) between the pump and signal the plot reveals a large amplification bandwidth ranging from 700 nm to 900 nm at a constant internal angle of about 22°. A tunable output can therefore be realized by temporally scanning the pump pulse across the chirped broadband signal in the BBO crystal. Figure 3(b) shows the resulting spectra when the time delay between signal and pump pulses is varied with a fixed pump tilt angle of 2.6° and a fixed crystal angle. In effect Fig. 3(b) shows a cross correlation of the chirped signal pulse with the much shorter pump pulse. The 18.3 ps measured between the time where the pump pulse overlaps with the narrow spectrum around 670 nm and the time when it overlaps with the broader spectrum around 970 nm therefore indicates the dispersion of the signal. To confirm this, a simulation of the pulse propagation through the 80 cm PCF was made by solving the extended nonlinear Schrödinger equation with a commercially available software[14]. Figure 4 depicts how the spectral region from 620 nm to 1040 nm of the simulated super continuum disperses relative to the pump wavelength at 1028 nm. A delay of roughly 18 ps between wavelengths around 670 nm and around 970 nm is observed in good agreement with the results presented in Fig. 3(b).

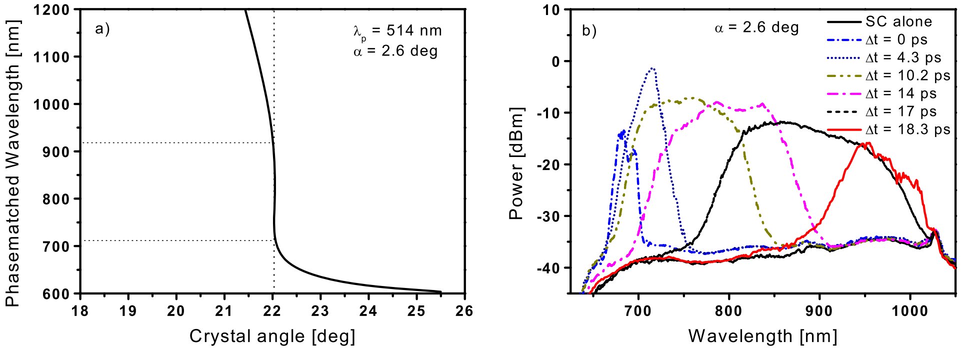

Fig. 3. a) Broadband phase-matching for a type I BBO crystal pumped at 514 nm with a pump tilt angle of 2.6°. b) Amplification in the wavelength range 650-1000 nm by changing the temporal delay between pump and signal.

The broadband phasematching, in this context, has significant influence on the duration of the amplified pulses as different delays cause spectral parts of different bandwidths to be sliced out by the pump pulse. Autocorrelation measurements have revealed pulse durations between 400 fs and 700 fs across the spectral range shown in Fig. 3(b).

3.2. Narrowband phasematching

When the pump-signal angle is different from 2.6° (internal), the phasematching properties change considerably. Figure 5(a) shows the calculated and measured phase-matching curves when the two beams form an angle of 4.9° (internal). Excellent agreement between experiment and theory is found for both signal and idler wavelengths and tunability in the range 700 nm to

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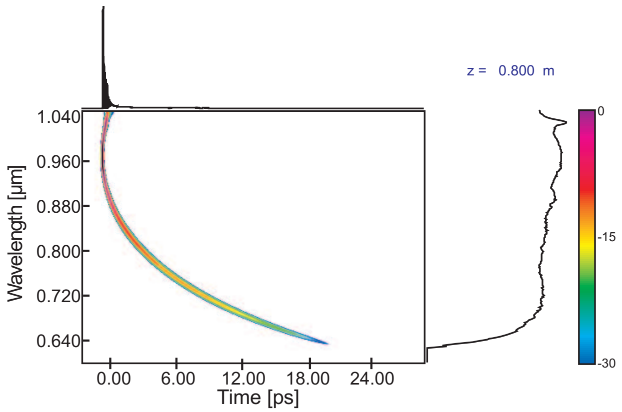

Fig. 4. Simulated spectrogram of the supercontinuum generated in 80 cm of the PCF for the spectral range of 620 nm to 1040 nm. Time is measured relative to the 1028 nm center wavelength.

1500 nm has been realized. The slopes in Fig. 5(a) illustrate that the phase-matching is spectrally narrow compared to the situation described above. The reduced phasematched bandwidth results in shorter pulses as only a small part of the spectrum is picked out by the pump pulse. Autocorrelations have shown pulse durations of 250-320 fs as depicted in Fig. 5(b).

Figure 6(a) shows the conversion efficiency for this configuration. At the highest conversion more than 1.2 W of average power, corresponding to a pulse energy of 1.2 μJ, has been obtained. At this power level, the pulse energy in the fiber amplifier is roughly 8 μJ and the resulting peak power causes a nonlinear phase contribution which is not compensated by the compressor. As a consequence, the duration of the compressed pulses increases and hence the pulse peak power decreases with pump power beyond this point. The lower trace in Fig. 2 shows the second harmonic power as function of pump power coupled into the amplifier fiber. The kink at 17 W of pump power marks the onset of pulse-lengthening.

Figure 6(b) and 6(c) show measured amplified beam profiles for two different conversion efficiencies. Due to the generation of the continuum in a photonic crystal fiber the signal has a Gaussian-like spatial profile. This is confirmed by the centro-symmetric mode shape at moder-

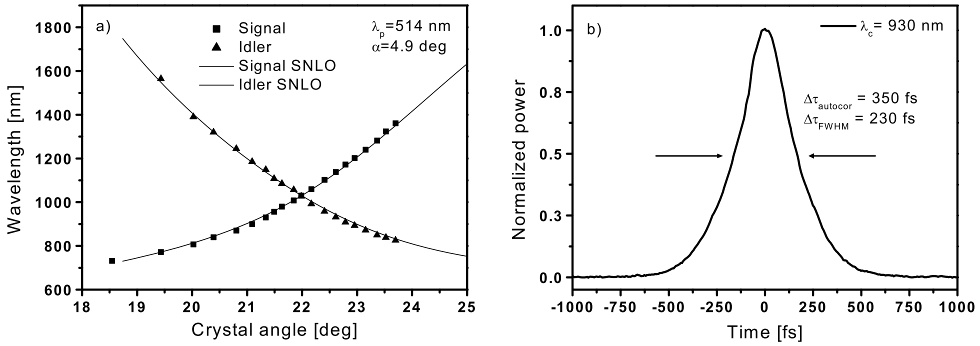

Fig. 5. a) Phasematching as found experimentally and calculated using SNLO software when the angle between pump and signal is 4.9°. b) Autocorrelation trace when the center wavelength is approximately 930 nm. The pulse has a FWHM of 230 fs.

ate conversion efficiencies. However, the beam profile deteriorates with increasing pump intensity and thus higher conversion efficiency. This can be explained by a saturation of the parametric amplification in the center of the beam which causes the mode to spread out in the direction of the highest gain, which coincides with the parametric fluorescence cone[15]. Depending on seed power, pump intensity and crystal length a compromise between conversion efficiency and beam quality has to be found. Figure 6(b) shows the beam profile recorded with a CCD-camera when a 30% conversion was obtained. Although the beam is slightly elliptical and the fluorescence cone is present, it is still of acceptable quality. Looser focusing of the pump beam always results in improved beam quality as illustrated in Fig. 6(c) where the pump spot size is increased to 150 μm. However, the conversion dropped to about 10% with this configuration.

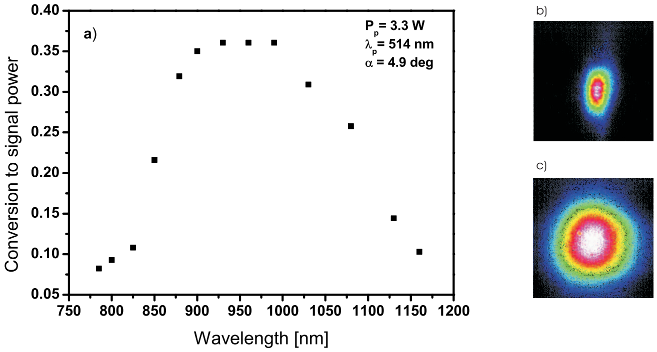

Fig. 6. a) Signal conversion efficiency at a pump power of 3.3 W at 514 nm. Right: Beam profile at b) 30 % and c) 10 % conversion. The difference in spot-size is due to different scaling of the images.

4. Short-pulse amplification

The large achievable phase-matching bandwidth of parametric amplifiers allows for the amplification of ultrashort laser pulses. Impressive results have been obtained in the this field and intense short, even few-cycle, pulses have been realized in the optical domain ranging from the UV to the NIR [6, 16, 17]. Such pulses are interesting for directly probing very fast phenomena but also for high-order harmonic generation resulting in ultrashort soft X-ray pulses[18].

Besides the well known benefits of parametric amplification of ultrashort laser pulse, such as the high gain, the enormous bandwidth and the negligible thermal load, there is one more important aspect making the combination of parametric amplifiers and fiber amplifiers attractive: In general, the performance of short pulse fiber amplifiers is limited by nonlinear pulse distortion. Self-phase modulation induces a nonlinear phase, hence the fiber based generation of high peak power transform-limited pulse is difficult. However, in a parametric amplifier the phase of the pump field is transferred to the idler field[19]. Consequently, the phase of the amplified signal is not distorted allowing for high quality phase compensation and the generation of ultrashort laser pulse even in the case of a distorted pump.

Broadband parametric amplification is possible in non-collinear geometry[16, 20, 21] or at degeneracy[22], as it is chosen in the experiment described herein. Besides few modifications, the experimental setup of the fiber laser pumped short-pulse parametric amplifier is similar to the scheme shown in Fig. 1. The AOM is placed before the stretcher and a beam-splitter is used to send 50% of the 1 MHz beam (50 mW) into just 9 cm of a standard single-mode step-index fiber (Flexcore 1060) while the remaining part is stretched to 50 ps and coupled

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into the same amplifier fiber as described above. The amplified pulses are recompressed and frequency doubled in a 1 mm BBO crystal. The SPM-broadened spectrum from the standard fiber is appropriately delayed before it is overlapped near-collinearly with the 514 nm pump in the 5 mm BBO crystal. With the crystal oriented for degenerate phase-matching the entire 85 nm broad spectrum is amplified as seen in Fig. 7(a). Figure 7(b) shows the autocorrelation trace of the amplified pulse after compression in a simple fused silica prism-sequence. The pulse-duration is reduced from initially 380 fs of the oscillator to 46 fs. With 3 W of green pump power a signal average power of 0.5 W corresponding to a peak power of 10 MW has been obtained. It should be mentioned that the autocorrelation is not affected by the parametric amplification. The wings in the autocorrelation trace, which contain a minor part of the pulse energy, have their origin in non-linear chirp imposed by SPM in the step-index fiber[23]. This behavior is confirmed by numerical simulations.

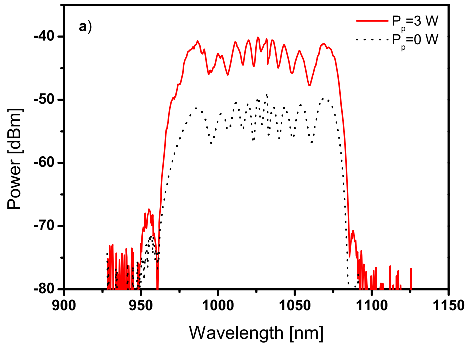

Fig. 7. a) Spectrum after 9.1 cm of standard fiber (dotted black) and after amplification in the BBO crystal (red). b) Autocorrelation trace of the 46 fs re-compressed pulse.

With this approach the tunability is limited to the spectral region around the pump wavelength of 1028 nm as the bandwidth is generated through SPM of the pump. This configuration is chosen to ensure a clean phase of the signal beam in order to allow re-compression to high quality pulses. When the broadband SC from the PCF is used as seed, it is not possible to significantly compress the pulses beyond what is shown in Fig. 5(b). This is due to the low coherence of the SC which is created mainly through soliton fission and four wave mixing. As a result, the SC consists of temporally separated features which can not be compressed to a single pulse[24]. It is however possible to create a coherent broadband signal by pumping the PCF below the threshold of soliton formation. In this case, the SC generation is dominated by SPM which allows re-compression of the amplified pulses. Reverting to the nonlinear geometry of the parametric amplifier (section 3.1) opens a gain window between 700-900 nm in which short pulse amplification can be realized. Experiments with such a setup are currently being pursued and will be reported later.

Future work will aim at improving the fiber amplifier in order to avoid the accumulation of nonlinear phase and the resulting pulse-broadening when operating at high pump powers. It is fairly straight-forward to solve this problem as it is simply a matter of reducing the peak-intensity in the fiber. With proper gratings and large-aperture optics it is possible to stretch the pulses to more than 1 ns as opposed to the 50 ps used here. The onset of pulse-broadening will then be pushed with factor of 20 or more. Additionally the amplifier fiber could be replaced with a short-length large mode area Yb-doped rod-type fiber[25] which can deliver the same gain as the present fiber but with significantly reduced nonlinearity. With relatively simple changes the fiber amplifier will be able to deliver compressible pulses at power levels many times higher than presented here. Using this concept as pump laser for a parametric amplifier will enable the generation of high repetition rate, and therefore high average power, high peak power ultrashort (potentially sub-10 fs pulses) laser pulses.

5. Conclusion

In conclusion, we have demonstrated an efficient optical parametric amplifier pumped by a fiber amplifier and have revealed the potential of this approach. Femtosecond pulses tunable from 700 nm to 1500 nm with a repetition rate of 1 MHz and pulse energies of more than 1 μJ have been obtained. The simplicity of the setup and the potential for power scaling makes this configuration an interesting alternative to traditional Ti:sapphire based NOPA-schemes and will find numerous applications in spectroscopy. Additionally, broadband parametric amplification at degeneracy and subsequent recompression to 46 fs pulse duration with peak powers above 10 MW has been demonstrated. Power scaling and further reduction of the pulse duration will be the focus of future work.

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